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OBSERVATION AND ANALYSIS OF PROTECTED MEMBRANE ROOFING SYSTEMS,(U)
APR 77 D SCHAEFER, E T LARSEN, H W AAMOT

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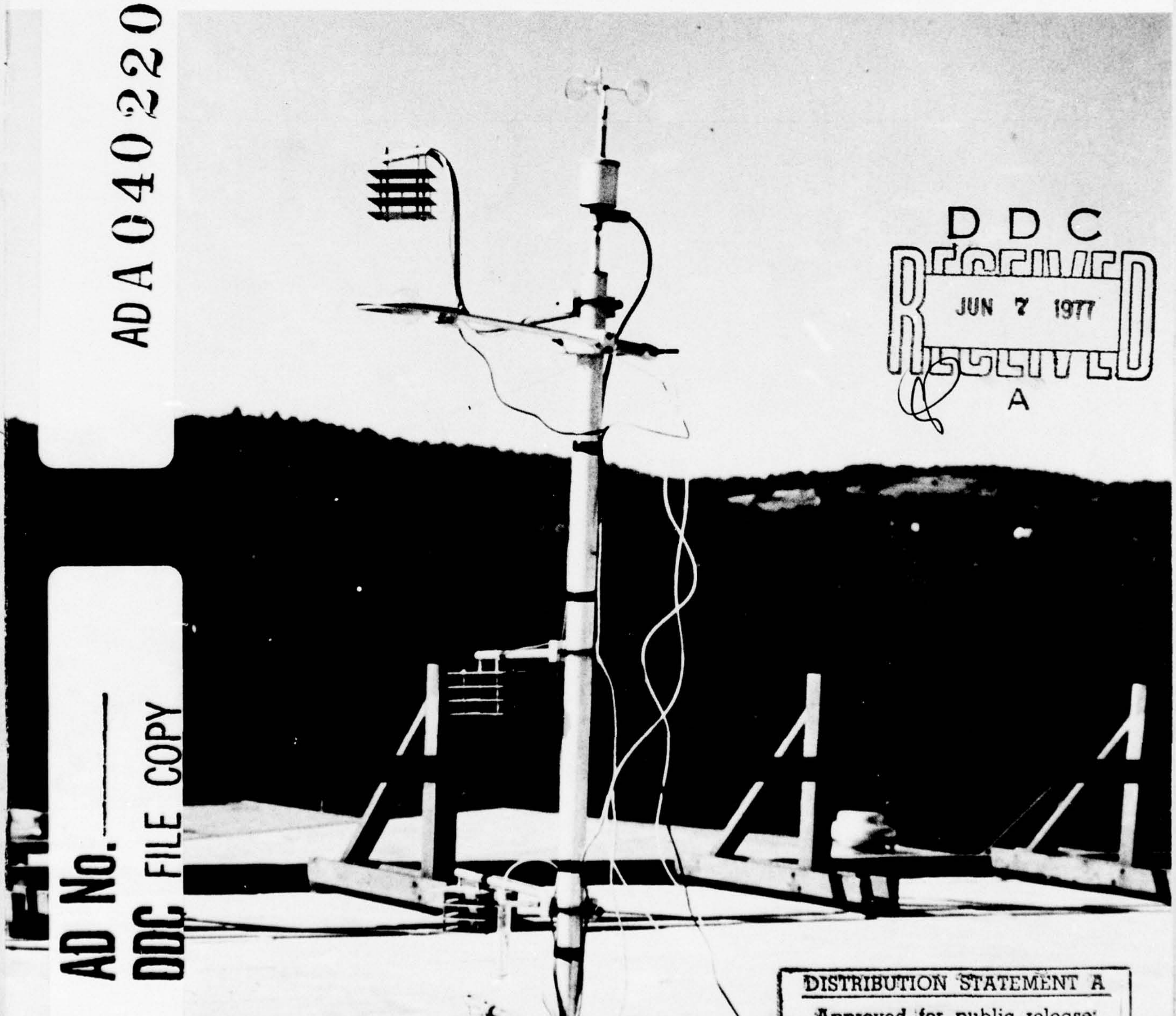

Cover: Instrumentation on protected membrane roof at Hanover, New Hampshire. (Photograph by Robert Demars.)

CRREL Report 77-11

Observation and analysis of protected membrane roofing systems

D. Schaefer, E.T. Larsen and H.W.C. Aamot

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Two performance indicators, effectiveness and thermal efficiency, are defined and used to evaluate the year-round performance of three protected membrane roofs in Alaska and New Hampshire. Effectiveness is a measure of the deviations of ceiling temperatures from a yearly average, with large deviations indicating erratic performance in the roofing-insulation system and small departures indicating a thermally stable system. Thermal efficiency, the ratio of calculated heat loss to measured heat loss, is affected by climatic conditions such as rain, snow, solar radiation and wind. Thermal efficiency values of 100% or greater are possible since the calculated heat loss is based only on the inside and outside air temperature differences and the thermal properties of the roof components. Results of the

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year-round evaluation indicate that the three protected membrane roofs generally have high values of both effectiveness and thermal efficiency.

PREFACE

This report was prepared by D. Schaefer and E.T. Larsen, formerly Research Civil Engineers of the Construction Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and by Dr. H.W.C. Aamot, Research Mechanical Engineer, also of the Construction Engineering Research Branch at CRREL. The work was funded by DA Project 4A162121A894, *Engineering in Cold Environments*, Task 21, *Cold Regions Building Systems for Military Installations*, Work Unit 004, *Evaluation of Protected Membrane Roofs in Cold Regions.*

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These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
$foot^2$	0.09290304*	$meter^2$
pound-mass	0.4535924	kilogram
pound-mass/$foot^2$	4.882428	kilogram/$meter^2$
Btu/ft^2	11356.53	joule/$meter^2$
$Btu/ft^2\ ^\circ F$	20.44175	$kJ/m^2\ K$
Btu/ft^2 day	0.1314412	W/m^2
Btu-in./$ft^2\ h\ ^\circ F$	0.1442279	W/m K

* Exact.

OBSERVATION AND ANALYSIS OF PROTECTED MEMBRANE ROOFING SYSTEMS

D. Schaefer, E.T. Larsen and H.W.C. Aamot

INTRODUCTION

For many years roofs of military structures have caused large maintenance problems, particularly in cold regions. For example, Cullen (1965) reported a 71.5% failure rate during a 7-year period for conventional bituminous built-up roofs at Alaskan military installations. As a result, CRREL was given the task of developing innovative roofing concepts that offered the best possibilities of reducing roofing failures in cold regions. The protected membrane roof system was chosen after careful study and theoretical analysis to be the most likely roof system to effectively replace the failure-prone built-up membrane roof system currently in use.

A research program was initiated to provide long-term performance characteristics based upon short-term evaluation. This type of research will enable promising concepts to be developed for use within relatively short time periods.

Several test roofs were constructed and instrumented to provide data for evaluation. It was considered necessary to gather the following types of data:

1. Temperatures of each component of the roof sandwich during different climatic conditions.

2. Heat flows into and away from each component to evaluate the thermal efficiency of the system and to estimate energy requirements.

3. Measurements of the microclimate above the roof to ensure performance in a wide range of climatic conditions and hence wide geographical adaptation of the system.

LOCATION OF TEST SITES

The protected membrane roof is different from conventional roofs in that the waterproof membrane is placed upon the structural deck and a waterproof insulation is loosely laid over the membrane and ballasted to prevent wind uplift. Several papers (Aamot 1972, Aamot and Schaefer 1970, Schaefer 1971, Schaefer 1974) have described the basic components of the roof in detail.

Since it was a prime consideration in the test and evaluation program to ensure that the concept would be suitable over a wide range of geographical locations, three test sites were selected which gave a wide range of possible climatic conditions.

Fairbanks

One test site was located near Fairbanks at Ft. Wainwright, Alaska. Fairbanks, located in interior Alaska, has a continental climate characterized by extremely cold winters and warm summers. Temperatures of -40°C are not uncommon during the months of December and January; summer temperatures of 25°C are not uncommon. Annual precipitation in this area is about 35 cm, of which 12 cm (water equivalent) falls as snow.

Anchorage

A test roof was built and instrumented at Elmendorf Air Force Base near Anchorage, Alaska. Near the ocean and surrounded by mountains, Anchorage experiences what is known as a maritime or coastal climate. The large mass of water tends to moderate the weather

conditions so that the winter temperature seldom goes below -28°C. The mean January temperature is -11°C and the mean July temperature is 14°C. Total annual precipitation for the Anchorage area averages 41 cm with approximately 16 cm (water equivalent) falling as snow.

Hanover, N.H.

Hanover is located in the Connecticut River Valley approximately 160 km inland from the Atlantic Ocean. The coldest month, January, has a mean temperature of –7°C while the warmest month, July, has a mean temperature of 20°C. Extreme warm temperatures above 27°C are not uncommon. The ground is covered with snow for about four months of each year compared to six months for the previous two locations. Precipitation of almost 100 cm falls per year, the majority as rain and less than 18 cm (water equivalent) as snow. (The photograph on the cover shows the instrumentation of the roof at Hanover.)

These three sites provided the wide variety of climatic conditions necessary for the successful evaluation of the protected membrane roofing system. To successfully recommend adoption of such a system it was necessary to show that these systems were economical, performed as predicted, and did not use increased amounts of energy. The testing of roofs in the above locations also ensured that the principles incorporated into this roofing system would be usable over much of the world.

TEST PROGRAM

A program was developed to evaluate the performance of low slope compact roofs by means of two quantitative indicators that permitted direct mutual comparison of all such roofs. This program also measured three qualitative indicators which provided engineering information and produced sufficient data to analyze heat budgets within the roof sandwich and thus calculate energy requirements.

In this program, the two quantitative performance indicators are described as: 1) *effectiveness* (a measure of the deviation of the ceiling temperature from its year-round average) and 2) *thermal efficiency* (the ratio of theoretical total heat exchange to actual total heat exchange). These two indicators are applicable to any low slope roof and serve as a measure of comparison between different roof sandwiches.

The three qualitative indicators providing engineering information are: 1) the effect of natural snow cover, which in some instances provides an added insulation at no extra cost, 2) the effect of water flow at the membrane level, which is the major factor in increasing energy requirements during some periods, and 3) the microclimate above the roof.

One of the major reasons for suggesting the use of protected membrane roofs is that the waterproof membrane stays in essentially an isothermal condition and is thus not subjected to thermal stresses. Monitoring the membrane temperature during various climatic seasons provides a measure of the variance in membrane temperature. The temperature of the top surface of a roof is expected to have a large seasonal and diurnal temperature fluctuation. In studies on pitched roofs the roof surface temperature was found to be as much as 40°C above the ambient air temperature. This fluctuation, of course, depends upon the emissivity of the surface material. Temperature measurements of the surface then give an indication of the extremes that a waterproof membrane at this level might be subjected to.

Often snow on a low slope roof is considered as free insulation. However, it can be considered such only if the 0°C isotherm always remains within the roof sandwich and does not rise into the snow pack. If snow is melted due to building heat, it can flow past the insulation to the membrane; thus a transfer of heat away from the roof causes a decrease in efficiency. The magnitude of this phenomenon can be properly determined by temperature measurements within the snow pack.

Heat flow between the building interior and the atmosphere is attenuated by the use of insulation. It is desirable to keep the heat flow from the interior of the building constant and as small as possible. During periods when radiant energy is great, the attenuation of heat flow from the atmosphere to the building interior is also desirable. Heat flows at the surface can be either positive or negative but should not materially affect the heat flow at the ceiling level. To measure these characteristics of a roof, heat flow meters are placed at the ceiling and at the top surface of the roof.

A heat budget analysis, using data generated from temperature and heat flow indicators, enables the researcher to determine how much energy is expended

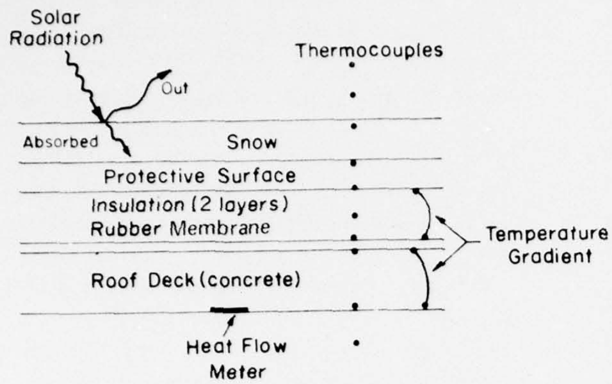

Figure 1. Location of monitoring instruments.

in such operations as evaporative drying of the insulation, heat transport due to water flowing on the membrane, and effective thermal conductivity of the insulation. Heat budget analysis is presented as a separate section of this report.

Climatic conditions to which each roof is subjected are important in the evaluation of roof performance. The cooling effect of rain and subsequent evaporation of water can be calculated only if precipitation measurements are made. Wind across a roof lowers the effective film conductances and increases heat flow from the building interior; radiant solar energy can decrease heating loads or, during summer, increase cooling loads. For these reasons it is necessary to measure all climatic conditions directly influencing the microclimate of the roof sandwich.

INSTRUMENTATION

Measurements were conducted over a year's period with data recorded continuously and automatically. Outdoor measurements of air temperature above the roof at various levels to 2 m, net radiation exchange, total precipitation, total incoming solar radiation, wind speed and direction, barometric pressure, and dew or frost point were obtained. Measured indoor conditions were air temperature and ceiling temperature and pressure. Conditions measured within the roof sandwich were heat flows at the ceiling and the top surface, the temperatures at various levels, and temperature gradients across various sandwich elements. Figure 1 shows a schematic diagram of the instrumentation used for measurement at the three test sites.

The primary instrument for measuring temperature and temperature gradients is the bimetallic thermocouple. The ease of installation and the capability of automatic reading make this one of the most important pieces of instrumentation for monitoring roof temperatures. The thermocouples selected were of the TTX type which are accurate to $\pm 0.42°C$. While better precision is attainable with other types of sensors (thermistors), the ease of calibration and recording makes the thermocouple more advantageous.

The heat flow meters were of the thermopile type. Special care was taken to ensure that the thermal impedance of the meter to the heat flow matched the impedance of the surrounding material. This ensured two-dimensional heat flow which is easier to evaluate by computer than are more complicated heat flow cases. Each heat flow meter sandwich was designed and constructed after thermal conductivity measurements of the surrounding material had been gathered.

Solar radiation and net exchange radiation were measured with shortwave solarimeters and net exchange radiometers. Electronic volt-time integrators were used to compute the radiation exchange. Since radiation exchange fluctuates significantly, the integrators count and add the sensor signals continuously and record results at periodic intervals. This method is more precise than computation based on periodic signal samples. The incoming shortwave radiometer covers the spectrum from 0.38 to about 3 μm wavelength. For this reason, readings with this instrument go to zero at night and it cannot measure the longwave radiation from the cloud cover. The net exchange radiometer provides a measure of the absorbed radiation. This is dependent upon the surface emissivity and changes seasonally due to snow.

EFFECTIVENESS

The effectiveness of a roof system was originally defined as the deviation of the ceiling temperature from its year-round average. However, for a protected membrane roof, deviations from the year-round average of the membrane, rather than the ceiling, were found to be more useful. This is an obvious departure from the original definition since the major reason for suggesting the use of protected membrane roofs is that the waterproof membrane is not subjected to the high thermal stresses experienced by conventional built-up roof membranes. When there is no insulation under the membrane, as in these test roofs, the membrane temperature and the ceiling temperature are fairly close to one another. In this case it is a safe assumption that, if the membrane does not deviate significantly from a year-round average temperature, then the ceiling temperature will not significantly depart from a year-round average.

The coefficient of thermal expansion for the Butyl and EPDM membranes used is about 1.8×10^{-4} per °C. A membrane situated on the top side of a roof would experience diurnal temperature variations of 45° to 55°C. Thus, for a 30-m roof the expected expansion/contraction would be about 0.27 m. It is desirable and necessary to reduce the magnitude of possible expansion/contraction by protection of the membrane.

Appendix A provides seasonal documentation of the variation of roof membrane temperatures of the Hanover, Fairbanks, and Anchorage roofs. Figure A1 illustrates winter conditions with a snow cover. The roof surface temperature during the 5-10 January 1973 period slowly drops from 1°C to -9°C. It is noticeable that during this same time the ambient air temperature drops from about 1°C to -29°C. During this same period the membrane and ceiling temperatures remain nearly constant at 20 ± 1°C.

During the period 29 January to 3 February (Fig. A2), two phenomena are observed: 1) there is a decrease in snow on the roof due to warm weather, and 2) there is 2.39 cm of rain. These combined effects lower the membrane temperature from 19.4° to 17.2°C. However, the membrane temperature does not suddenly drop but requires a 24-hr period. The ceiling temperature closely follows the membrane temperature.

When the ambient temperature rises and the protective snow cover is no longer on the roof, the roof surface temperature fluctuates as much as 39°C. The period 10-27 April 1973 (Fig. A3) shows this effect. While diurnal temperature changes of the abovementioned magnitude take place on the roof surface, the membrane temperature is 21°C ± 2°C. The membrane shows only slight diurnal variations and the change in temperature is due primarily to a steady decrease in the snow cover. During the first four days of this period the last snow is melting from the roof. Once the snow cover is completely melted, the membrane temperature begins to rise slowly. The roof surface temperature fluctuations are greater than the air temperature due to large diurnal solar radiation inputs.

The protective ballast on the test roofs is concrete pavers. Inputs of solar radiation cause the surface temperature fluctuations to be significantly greater than the diurnal air temperature variations. If the absorptive characteristics of the surface were changed, then the expected surface temperature variation would change. It was beyond the scope of this program to measure effects of solar absorption as a function of surface characteristics. However, when the surface of the roof is a built-up membrane, daily fluctuations in temperature would be at least as great as with the concrete pavers.

In general, the membrane temperature fluctuations over an entire year were ± 6°C at the test sites. The amplitude of diurnal temperature changes was effectively dampened by the insulation. Hence, the membrane was unaffected. The major contributions to membrane temperature rise or fall from the year-round average of 21°C were long periods of cold or warm weather. During the summer, the average membrane temperature could be expected to be above 21°C, while during winter, the temperature would be below 21°C. The membrane temperature closely follows the indoor temperatures, and fluctuations in indoor temperature cause the major fluctuations in membrane temperature.

THERMAL EFFICIENCY

The thermal protection that is offered by a roof is characterized by its U-value (overall heat conductance). The U-value includes the thermal conductance of the materials of the roof (in the case of a low slope, compact roof) and also the heat transfer coefficients between the air and the roof, both inside and outside.

The U-value is a useful criterion for general guidance in finding the insulation requirements of a roof. It is less useful for evaluating the roof's energy losses. These

are influenced by factors that are not adequately considered by a single U-value, such as sunshine, wind, rain and snow. Thus, different roofs of equal U-values can have different energy losses. However, reducing energy losses is a basic objective of roof construction.

It is quite easy to specify a U-value for a given geographical location and to calculate the U-value of a planned or an existing roof. It is more difficult to determine a roof's actual energy losses. The effort is worthwhile when the roof, or the number of roofs, involved is large and when the climate is severe, resulting in large energy requirements and costs.

The heat transfer through the roof can be calculated from the indoor and outdoor temperatures and the U-value. This may be called the *theoretical energy loss.*

The theoretical energy loss is computed from the U-value which is based on the inside and the ambient air temperatures and the thermal properties of the roof sandwich. The U-value of the roof sandwich is computed by addition of the thermal resistances of its component parts:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{z_1}{k_1} + \ldots + \frac{z_n}{k_n} + \frac{1}{h_2}$$

where h_1 = inside film conductance
h_2 = outside film conductance
z_n = thickness of each component
k_n = thermal conductivity of each component.

While this formula implies steady-state conditions it is widely used by designers to compute expected heat losses from roofs by the formula:

$$Q = U \Delta T$$

where Q is total heat and ΔT is the expected difference between indoor and outdoor temperature. Data on the thermal conductivities are available in engineering handbooks or from manufacturers' literature. The film conductance h_2 is dependent upon the wind at the particular roof location. Generally for design purposes a 24-km/h wind is used. The theoretical energy loss is then, in essence, a constant value. It does not take into account varying wind speeds, solar radiation inputs, rain and other factors which affect the actual energy losses from a roof but only considers the temperature difference.

The measurement of actual energy loss can, however, differ significantly from theoretical calculations. Solar radiation influences the heat transfer in one direction, nocturnal radiational cooling in the opposite direction. Wind and rain also affect actual energy loss, and snow often provides natural insulation. Another type of influence affecting the actual heat transfer is the dynamic thermal response of the roof to the weather conditions. This response is influenced by the different thermal properties of the various components of the roof: the structural deck, the insulation, etc.

The dynamic thermal responses of different roof designs can lead to different energy losses, other factors being the same. Computation of actual energy loss is by calculation of hourly heat transfer for given weather conditions and summation, over a period of time, by computer. Lower actual losses mean greater *thermal efficiency*, and vice versa. The thermal efficiency η is defined (Aamot 1971) as the ratio (expressed as a percentage) of theoretical to actual energy loss:

$$\eta = \frac{\text{theoretical energy loss}}{\text{actual energy loss}} .$$

An analysis of the equation shows that thermal efficiency may be either greater than, equal to or less than 100%. Greater efficiency means simply that the actual energy loss is smaller than the theoretical loss. This occurs, for example, during cold sunny weather. The efficiency decreases when rain and wind cause greater heat loss than theoretically predicted.

Heat loss due to cold weather is an actual energy loss as is heat gain during hot weather. In the first case, the energy loss represents a heating requirement, in the second case, a cooling requirement. The annual energy loss is the sum of all heating and cooling requirements over a one-year period. It is this figure that is of basic interest.

The thermal efficiency over a one-year period is a measure of the performance of a roof in a given location, or more precisely, under certain given climatic conditions. It is a value that is independent of the design and behavior of other roofs and, therefore, permits a comparison of roofs of different design.

Essentially the measurement program was designed to collect data on the actual energy losses and to evaluate the climatic factors which most materially change them. Thermal efficiencies of 100% or more

were achieved on cool days when solar radiation provided energy. Conversely efficiencies less than 100% were expected and achieved during and shortly after rain storms.

Appendix B provides monthly summaries of the thermal efficiencies for the test roof sites. Several interesting phenomena are shown by these graphs:

1) *Thermal efficiency is affected by rain.* The theoretical energy loss on 6 October 1972 at Hanover (Fig. B1) was 322 kJ/m^2; the actual energy loss measured by the heat flow meter at the ceiling was 137 kJ/m^2. A thermal efficiency of 244% was thus achieved. The following day had about the same air temperatures but 4.6 cm of rain fell and the actual heat loss was 486 kJ/m^2. The thermal efficiency was then rapidly reduced to 57% because convection heat transfer at the membrane occurred. This same phenomenon also applies to melting snow (16-24 November, Hanover roof). On 16 November (Fig. B2) there was 10.2 cm of snow on the roof. This snow depth gradually decreased to zero by 24 November and the thermal efficiency again was below 100% for this same time period.

2) A nonmelting snow cover does not lower the thermal efficiency. Figure B4 illustrates this for the Hanover roof. From 4 to 18 January, the snow cover was a constant 38 cm yet the thermal efficiency was above 100%. After 18 January, rain and melting snow combined to lower the efficiency below 100%.

3) Wind is not an important factor in reducing the thermal efficiency. The film conductance h_2 is dependent upon wind velocity. Wind does, however, have a great effect on the cooling of the upper surface. The effect of wind on the overall U-value of the roof is slight. Increasing wind speed from 3.35 m/s to 6.7 m/s increases h_2 from 23 to 37 W/m^2 °C. This changes the total U-value of the roof by about 0.5%.

4) High solar radiation increases the efficiency. In August 1973 (Fig. B11) the thermal efficiency of the Hanover roof was above 100% for almost the entire month despite eight days with rain. The solar radiation was significant in keeping the efficiency high.

Thermal efficiency is an effective measure of the performance of a roof. Measurements taken during the test period are useful in determining the actual effects of various climatic factors on the heat transfer of the roof system.

HEAT BALANCE WITHIN THE ROOF

As part of the program to evaluate the thermal performance of the protected membrane roof design, it was decided to undertake a heat budget analysis of the Hanover roof structure, utilizing the massive amounts of data collected.

Certain decisions were made in order to simplify the analysis, the first being that the analysis should be of heat balance within the roof, encompassing the roof deck, the rubber membrane and the Styrofoam insulation. This would eliminate the need to take into account the surface convection, both natural and forced, and the effects of solar radiation. Both of these are extremely difficult to calculate accurately. Also, the analysis was performed only during the spring, summer, and fall, eliminating the problem of the effects of snow cover.

All calculations were performed and results presented using the English System of Units, rather than the SI system used throughout this report. This is done because all data were recorded using this system. The English System also allows the analysis to be simplified by dealing with a 1-ft^2 area. Further, the results of this analysis deal with the effective *thermal* conductivity of the Styrofoam insulation, which is conventionally presented in Btu in./ft^2 °F hr. By using these same units, the reader will have a better "feel" for the changes incurred in the thermal conductivities.

The main reason for undertaking this analysis was to determine how much of an internal cooling effect can be attributed to rainwater runoff and evaporative cooling.

A simplified model of the heat flow phenomena occurring within the roof sandwich is shown in Figure 2. From this model, the internal heat balance of the roof structure can be seen to be

$$\Sigma Q_{in} = \Sigma Q_{out} + \text{enthalpy change} \quad (1)$$

$$Q_1 = Q_2 + Q_3 + Q_4 + \Delta h \, . \quad (2)$$

In the case of heat loss as shown in Figure 2, $Q_{in} = Q_1$ and $Q_{out} = Q_2$.

Taken individually, the components of the heat flow equation and their derivations are as follows.

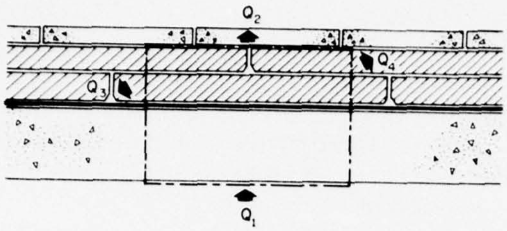

Figure 2. Boundaries for the balance of heat flow in the protected membrane roof.

Q_1 = heat flow into the system. This is a measured quantity, determined through the use of the heat flow meter placed in the ceiling. Q_1 is measured in terms of Btu/ft^2 day. Using a predetermined sign convention, positive heat flow is defined as heat flow downward from the roof deck into the room.

Q_2 = heat flow out through the insulation. This is an indirectly measured quantity. The temperature difference across the insulation is measured and the corresponding heat flow is determined from the relationship:

$$Q = C\Delta T. \tag{3}$$

In this equation, C is the thermal conductance of the Styrofoam insulation, and is derived from the k-value, or thermal conductivity, of the insulation and its thickness:

$$C = k/z \tag{4}$$

where k = 0.20 Btu-in./ft^2 hr °F for Styrofoam
z = 3¼ in. = thickness of insulation
C = 0.061 Btu/ft^2 hr °F = overall conductance.
For a 24-hr period: C = 1.464 Btu/ft^2 °F day.

Q_3 = internal water cooling from rainwater and meltwater runoff. This is a mass transfer problem involving the amount of rainfall m, the specific heat of water C_p and the rise in temperature of the water as it travels through the roof to the internal drains. Therefore:

$$Q_3 = mC_p\Delta T \tag{5}$$

where m is the precipitation rate and C_p the specific heat. Used as a baseline, 1 in. of rainfall falling on a 1 ft^2 area would result in

$$m = \frac{1 \times 62.4}{12} = 5.2 \text{ lbm water/ft}^2$$

$$C_p = 1 \text{ Btu/ft}^2 \text{ °F lbm}$$

$$mC_p = 5.2 \text{ Btu/ft}^2 \text{ °F, for 1 in. of rainfall.}$$

From this it is a simple matter to calculate the heat loss per degree Fahrenheit temperature change due to any amount of rainfall. The rise in temperature of the water is determined from the temperature of the roof surface and the drain during the period of rainfall.

Q_4 = evaporative heat transfer. This is the most difficult component of the heat balance equation to determine, as it cannot be measured accurately and must be determined from the mass of water evaporated and the change in enthalpy during vaporization of water. The difficulty occurs in determining the amount of evaporation which takes place. A suitable empirical equation for calculating Q_4 is not known. Since the drainage from the test roofs is fairly swift, it is improbable that more than 0.01 in. of water would be left upon the membrane after a rainfall. A better first estimate might be 0.008 in. If this is the case, there would be 0.0416 lbm of water per square foot of surface area, with the heat of vaporization of water h_{fg} being 1055 Btu/lbm. The total evaporative heat transfer after each rainfall would be on the order of 40 Btu/ft^2. By inspection of the roof sandwich it has been found that, in most cases, the evaporative process will be complete within two days after the rainfall. Therefore, as an estimation for purposes of this analysis, two days of evaporative drying will be used following each rainfall with 20 Btu/ft^2 being allotted for each day.

Δh = enthalpy change within the roof structure. The thermodynamic concept of enthalpy is related to the change in internal energy within a system, in this case the roof structure during a 24-hour period. The enthalpy change of the roof during a 24-hour period is determined in the following manner:

$$\Delta h = mC_p\Delta T. \tag{6}$$

The three components of the roof structure are:

1) The deck, which consists of 5 in. of concrete, m = 60 lbm/ft^2, C_p = 0.21 Btu/lbm °F:

$$\Delta h_{deck} = 60 \times 0.21 = 12.6 \text{ Btu/ft}^2 \text{ °F}.$$

2) The insulation, 3¼-in. extruded polystyrene foam boards, $m = 0.54$ lb/ft^2, $C_p = 0.27$:

$$\Delta h_{ins} = 0.54 \times 0.27 = 0.146 \text{ Btu/ft}^2\ ^\circ\text{F}.$$

3) The membrane, $^1/_{16}$-in. EPDM sheet, $m = 0.383$ lb/ft^2, $C_p = 0.45$:

$$\Delta h_{membrane} = 0.383 \times 0.45 = 0.172 \text{ Btu/ft}^2\ ^\circ\text{F}.$$

Since the Δh attributed to both the membrane and the insulation is so small compared to that of the concrete deck, it can be ignored and the composite value of $\Delta h = 12.6\ \Delta T$ can be used. The value of ΔT is the change in the roof deck temperature during a 24-hour period.

The final summation of the heat balance for each in.^{2} of roof, then, takes this form:

Q_1	Ceiling heat flow meter reading (in Btu/ft^2)
$-Q_2$	-1.464 Btu/ft^2 (ΔT across insulation)
$-Q_3$	-5.2 Btu/ft^2 (amount of rainfall) $\times$ (ΔT rainwater)
$-Q_4$	-40 Btu/ft^2 (2 days after each rainfall at 20 Btu/ft^2 day)
$+\Delta h$	$+12.6$ Btu/ft^2 (ΔT deck)
	$\Sigma = 0$

The months of October 1972 and March through September of 1973 were selected for the heat balance analysis. As earlier stated, no winter months (except March) were used in order to avoid the problems caused by snow cover, such as the meltwater runoff and the effects of sublimation of the snow cover, which could not be accurately measured with the existing instrumentation.

Daily summations of the heat balance were made and the monthly totals tabulated. Table I shows these totals. The last column represents the amount by which the equation fails to balance.

Several things can be seen from this heat flow summation. First, evaporative cooling is a significant contribution to the internal heat balance of the roof, being on the order of 150 Btu/ft^2 month.

Secondly, rainwater runoff can be a significant factor, particularly during the months of May and June, during each of which approximately 5.5 in. of rain fell. During the other six months of the analysis, rainfall on the order of 1.5 to 2.5 in. per month was recorded. In these cases, although the contribution was smaller, it was by no means a negligible factor.

The third, and most important, phenomenon to come out of the summation is the fact that the equation does not usually balance; there is usually a certain amount of residual heat.

In the cases of October, April, July, August and September, the residual heat is small, being on the order of 20 Btu/ft^2 over a month-long period, while the total heat flow, both positive and negative, is on the order of 500-1500 Btu/ft^2. However, during the months of March, May and June the heat flow is significantly larger and must be accounted for in the heat balance; that is, the heat balance must be driven to zero.

Upon examination of the heat balance equation, all the factors are either measured directly or are calculated from basic heat flow equations. The least precise component of the equation is the amount of cooling attributed to evaporation, but if it is assumed, for the moment, that the proper assumptions have been made and that the estimation is correct, there is only one factor which can be changed to balance the heat budget. This factor is the thermal conductivity of the Styrofoam insulation. While the accepted k-value for extruded polystyrene is 0.20 Btu/ft^2 hr $^\circ$F, it is also known that the conductivity of the insulation will change in accordance with certain factors, the most significant being moisture pickup.

A first estimation of the change in the k-values can be easily obtained. Since the residual heat for each month-long period is known, and it has been assumed that the k-factor is the only factor subject to change, a simple proportion can be set up to determine what k-factor will provide the change in heat flow characteristic necessary to force the equation to zero. The adjusted k-value is designated k^*.

$$\Delta Q_2 = \text{residual heat } RH$$

$$\frac{k^*}{0.2} Q_2 = Q_2 + \Delta Q_2 \text{ (change in } Q_2 \text{ due to changing } k\text{-value from 0.20 to } k^*)$$

$$\Delta Q_2 = Q_2 \left(\frac{k^*}{0.2} - 1\right) = \text{residual heat}$$

$$\frac{k^*}{0.2} = \frac{RH}{Q_2} + 1$$

$$k^* = 0.2\left(\frac{RH}{Q_2} + 1\right). \qquad (7)$$

Table I. Internal heat balance by month (Btu/ft^2 month).

Date	$+Q_1$	$-Q_2$	$+\Delta h$	$-Q_3$	$-Q_4$	*Residual heat*
Oct 72	− 927.1	−798.6	−51.2	− 36.3	−180.0	+ 36.6
Mar 73	−1412.3	−900.8	+38.4	− 74.2	−160.0	−238.9
Apr 73*	− 531.9	−433.4	0	− 83.6	− 40.0	+ 25.1
May 73	− 906.4	−475.1	−22.0	−178.8	−140.0	−134.5
June 73	− 148.1	+ 0.9	−38.4	−150.7	−180.0	+143.3
July 73	+ 128.8	+355.5	+38.4	− 39.0	−140.0	− 9.3
Aug 73	− 2.0	+189.6	−22.8	− 40.8	−140.0	− 33.6
Sept 73	− 467.2	−353.6	−38.4	− 28.9	−140.0	+ 16.9

* Based on 18 days – 13-30 April.

The results shown in Table II seem to correspond to expected tendencies. Since the major factor affecting the insulation's thermal conductivity is expected to be moisture pickup, the *k*-value should, theoretically, be higher during months when large amounts of water flow through the roof structure. In March, large amounts of meltwater runoff would be expected after a winter-long snow cover, and the corresponding thermal conductivity is high at 0.253. During the month of April, relatively little rainfall was experienced ($\approx$ 1 in.) and a general warming trend served to dry out the insulation, causing the *k*-value to fall down closer to the insulation's "book-value" at 0.194.

When this equation was applied to the heat balance, the following are the resulting first estimates obtained for k^*.

Table II. First estimates of adjusted *k*-values of Styrofoam insulation.

Date	k^*	$\%\Delta k$
Oct 72	0.191	− 4.5
Mar 73	0.253	+26.5
Apr 73	0.194	− 3.0
May 73	0.256	+28.0
June 73	0.213†	+ 6.5
July 73	0.195	− 2.5
Aug 73	0.188	− 6.0
Sept 73	0.192	− 4.0

† Since the sum of the heat flow across the insulation was so small for the month of June, k^* could not be calculated over a month-long period. Instead, four-week periods were isolated and the resulting *k*-values averaged to give k^*.

Again the conductivity increases during the months of May and June, when large amounts of rainfall are experienced (5.5 in. each month), and begins to fall off again during the remainder of the summer when relatively dry weather is experienced. This indicates that while moisture pickup during wet months does affect the thermal conductivity of the insulation, there is no long-term degradation of the foam during the first year after installation.

There is no exact method of determining the validity of either the effect of evaporative cooling or the change in thermal conductivity with moisture. However, it is safe to assume that these two factors are the only two which can change enough within the heat balance equation to affect the amount of residual heat observed. It was decided, then, to try several different values for evaporative cooling in order to test the effect each would have on the residual heat and in turn on the thermal conductivity value assigned to the insulation. The following schemes were investigated:

1) Two days drying at 20 Btu/ft^2 day plus one day at 10 Btu/ft^2.

2) One day drying at 20 Btu/ft^2 plus one day at 10 Btu/ft^2.

3) Four days drying at 15 Btu/ft^2 day.

The results are shown in Table III.

Two general conclusions can be made from an examination of Table III.

First, the reference being used was an evaporative cooling contribution of 20 Btu/ft^2 day for two days of drying following each rainfall. The effect that changing this value has upon the heat balance and, consequently, the calculation of the thermal conductivity for the particular period depends upon the

Table III. Effect of various evaporative cooling schemes on the calculation of thermal conductivity of the Styrofoam insulation.

Date	2 days (20 Btu/ft^2 day) (k^*)	2 days (20 Btu/ft^2 day) 1 day (10 Btu/ft^2 day) (k^*)	(%Δ)	1 day (20 Btu/ft^2 day) 1 day (10 Btu/ft^2 day) (k^*)	(%Δ)	4 days (15 Btu/ft^2 day) (k^*)	(%Δ)	Heat flow across insulation
Oct 72	0.191	0.183	− 4.2	0.198	+ 3.7	0.168	−12.0	− (↑)
Mar 73	0.253	0.246	− 2.8	0.261	+ 3.2	0.249	− 1.6	− (↑)
Apr 73	0.194	0.194	0	0.198	+ 2.1	0.198	+ 2.1	− (↑)
May 73	0.256	0.248	− 3.1	0.265	+ 3.5	0.246	− 3.9	− (↑)
June 73	0.213	0.213	0	0.213	0	0.213	0	+ (↓)
July 73	0.195	0.212	+ 8.7	0.178	+ 8.7	0.234	+20.0	+ (↓)
Aug 73	0.188	0.228	+21.2	0.143	−24.0	0.212	+12.8	+ (↓)
Sept 73	0.192	0.173	− 9.9	0.207	+ 7.8	0.168	−12.5	− (↑)

direction of the heat flow across the insulation. This heat flow is generally upward, or negative, during the cooler fall and spring months, and downward (positive) during the warm summer months. Increasing the estimated evaporative cooling during the cool months (negative heat flow) causes a drop in the calculated thermal conductivity, while an increase during the summer months (positive heat flow) causes this k-factor to become larger. The opposite effect occurs when the evaporative effects are decreased. This follows logically from the heat balance equation and indicates that the calculated k-values are, at least, of the right order of magnitude.

A second general observation is that the three alternate evaporative cooling schemes investigated seem to lead to thermal conductivity values that are less probable than the reference scheme. While there is no way of determining the upper limits to place on the thermal conductivity values, low values such as 0.168, 0.143 and 0.173 can be discarded. This leads to the alternative of abandoning the schemes for changing the evaporative cooling effect from two days at 20 Btu/ft^2 day.

Two major conclusions were gained from the heat study.

1) The thermal conductivity does change in accordance with moisture pickup. Over the first year after installation, however, no long-term degradation has been experienced. The values cited in Table II are valid.

2) Rainwater and meltwater runoff are significant contributions to the internal cooling of the roof structure. A more significant effect, however, is that of evaporative cooling. A good estimate of this cooling effect is that two days of drying are incurred following each rainfall, each day consuming 20 Btu/ft^2.

COMPARISONS WITH CONVENTIONAL SYSTEMS

During the testing phase, instrumentation similar to that in the protected membrane roof was installed at another location in Hanover, N.H., on an adjacent conventional five-ply built-up roof with a gravel surface. This conventional roof had 2 to 5 in. of foamed concrete insulation between the concrete deck and the built-up asphalt membrane. Data from this location were compared with those from the protected membrane roofing and observations on the behavior of each roof were noted. Graphs in Appendix C show the performance for selected periods during the year.

The bitumen surface of a built-up roof follows diurnal temperature fluctuations. Inputs of energy, primarily solar, often act to make the roof surface warmer than the ambient air. A primary reason for suggesting the use of protected membrane roofing systems is that the waterproof membrane remains in an isothermal condition year-round and is not subjected to diurnal temperature fluctuations; hence it is not subjected to extreme thermal stressing.

The linear coefficient of expansion of an asphalt and felt roofing membrane varies from approximately 36×10^{-6} to 72×10^{-6} per °C, for an average of 54×10^{-6} per °C across the width of the roofing felts. It is somewhat less for the lengthwise direction of the felts. Thus for 30.5 m of roofing membrane and a temperature change of 55°C, an unrestrained roofing membrane will contract 9.14 cm. The significant factor, then, becomes the regularity with which the roof experiences temperature changes of this magnitude.

Figures C1-C4 show comparisons of conventional asphalt built-up roofing systems and protected membrane systems. During January 1973 the diurnal temperature changes on the surface of the built-up membrane averaged 16°C. The maximum daily temperature change was 28°C. For one week's period the lowest surface temperature was -28°C and the highest temperature was 7°C.

For a similar January 1973 period the protected membrane roof membrane remained at 20°C ± 3°C. This is just slightly below the room air temperature. There are no diurnal variations noticeable since the thermal properties of the insulation isolate the membrane.

A period in August 1972 was selected to represent typical summer conditions. The diurnal temperature variation of the conventional roof was as much as 43°C for 31 August. The roof surface reached a maximum temperature of about 54°C on this day. Figure C3 shows this characteristic of the roof. It is also noticeable that the roof surface temperature is considerably higher than the ambient air temperature. On 31 August the ambient air temperature was 29°C and yet the roof surface temperature reached 54°C. In general this was due primarily to solar radiation.

During the same period the protected membrane roof membrane averaged 26.6°C ± 4°C. Again the stability of the membrane temperature is closely associated with the room temperature and not with diurnal temperatures. The concrete surface temperature fluctuates with daily air temperatures and exceeds ambient temperatures just as the built-up membrane, but the loose-laid concrete pavers can expand and contract freely.

On a diurnal basis surface temperature changes of 55°C are possible with asphalt built-up membranes. The conventional built-up roof at CRREL showed a temperature range of 10 to 55°C on 31 August 1972 (Fig. C3). If the roof surface is not gravel covered, even greater (and more rapid) temperature changes are possible. Gravel coating reduces the absorbed solar radiation and associated heating effects. The protected roof membrane is not subjected to diurnal temperatures if the building enclosure remains at a constant temperature. If, however, the building enclosure is open to the atmosphere and the temperature is allowed to fluctuate with the ambient air temperature, the protected membrane will also fluctuate (see Fig. A6). It will not, however, be subjected to radiant solar energy inputs.

Temperature variations in excess of 55°C on a yearly basis are certain for conventional roofing. During the testing phase extremes in surface temperature variation of 84°C were noted on a one-year basis. Figures C1 and C3 show temperature extremes of −20° and +130°F (−29° and +55°C).

CONCLUSIONS

The test program was designed essentially to gather extensive information in order to facilitate an analysis of the performance of the protected membrane roofing design. This information was of two categories: thermal performance and heat flow characteristics.

Effectiveness of the test roof

The thermal performance results from the Hanover protected membrane roof show that, under widely varying air temperatures (−32°C to +32°C), the roof surface temperature can vary by as much as 86°C (−32°C to +55°C) over a one-year period. They further show that during the hot summer months the surface temperature can vary by as much as 47°C during a single 24-hour period. The roof surface temperature is affected by such climatic factors as snow cover, rainfall, wind speed and amount of solar radiation received, and it can be seen that a tremendous thermal stress is imposed upon the roofing materials.

During the same time period the range of the waterproof membrane temperature is from 19°C to 28°C, a variation of 9°C over a one-year period. This represents the extremes of temperature experienced by the membrane, but the normal variation is much less in many cases and often an entire month passes with the membrane temperature varying only 1°C. The membrane temperature is much less influenced by climatic conditions than the surface. The only factor which does influence it to any degree is rainwater or meltwater runoff, which has a cooling effect.

The effectiveness of the protected membrane roofing design has been defined earlier in this report as a performance indicator measuring the deviation of the membrane temperature from its yearly average. Based

on this criterion, it is evident that the design concept does, indeed, perform adequately in protecting the waterproof membrane from the thermal stresses imposed on a conventional built-up roof surface.

Thermal efficiency

The heat flow characteristics of the test roof have been discussed in this report and graphic examples are included in Appendix A. The most important findings of the heat flow analysis are in terms of the roof's thermal efficiency.

Thermal efficiency η has been defined as the ratio (expressed as a percentage) of the theoretical to actual energy loss:

$$\eta = \frac{\text{theoretical energy loss}}{\text{actual energy loss}} \quad .$$

The efficiency of the roof is greater than 100% during most of the year, and is affected either beneficially or detrimentally by the following climatic conditions.

1. Rainfall and meltwater runoff cause internal cooling and thus decrease the thermal efficiency during cold weather. Rain during hot weather can reduce heat gain through the roof and improve its thermal efficiency.

2. Solar radiation tends to increase the roof's thermal efficiency during cool weather as it supplies a free heating input.

3. Snow cover provides an added insulating effect, cutting down the energy loss through the roof and increasing the thermal efficiency.

4. Wind convection, although a significant contribution to the surface heat balance, has little internal cooling effect and does not alter the thermal efficiency appreciably.

Heat balance within the roof

The internal heat budget analysis concluded that the thermal conductivity factor of the Styrofoam insulation varies by as much as 20% from its stated value when installed. This variation is caused by moisture pickup during periods of heavy rainfall. However, upon drying, the Styrofoam returns to its original conductivity and no long-term degradation has yet been experienced.

It was also concluded that rainwater and meltwater runoff have significant cooling effects on the internal roof structure. These effects are due both to mass transfer over the membrane surface and to evaporative drying. One inch of rainfall is equivalent to 5.2 lb of water/ft^2 and upon warming by approximately 1 to 2°C, it incurs a cooling load of 18.2 Btu/ft^2. Evaporative drying has been estimated to cool the roof structure at a rate of 20 Btu/ft^2 day for a two-day period following a rainfall. Of these two factors the evaporative drying is by far the largest effect.

While this internal cooling effect due to rainfall does represent a significant energy requirement in certain circumstances that are not present in a conventional built-up roof, it has been shown that, due to the added insulating effect that can easily be achieved with this design, significant energy savings can be realized with only the comparatively small cost of added insulation. This cost can be easily defrayed in a matter of years through energy savings. Also, the protected membrane roof does not trap and collect water.

Applicability

The protected membrane roofing design was developed for use in cold regions such as Alaska and other northern areas. However, it is also applicable to temperate climates, such as are found in the continental United States, and could easily be used in reducing the degenerative effects of hot, humid climates on built-up roofs.

RECOMMENDATIONS

Over the one-year period, the protected membrane roofing design has been shown to perform well, in that it provides an effective and efficient thermal barrier. While it is realized that a one-year test program does not ensure long-term success, all indications are that the roof will perform adequately and provide the added benefits of an extended lifetime and reduced maintenance expenses.

It is therefore felt that the protected membrane roofing design is a feasible alternative to the conventional built-up roof and should be adopted selectively by the U.S. Army Corps of Engineers for future low slope roof construction, particularly in cold regions.

LITERATURE CITED

Aamot, H.W.C. (1972) Developments in flat roofs for cold climates. CRREL Internal Report 277.

Aamot, H.W.C. and D. Schaefer (1970) Roofs for cold regions. *The Military Engineer*, May-June.

Cullen, W.C. (1965) Performance of roofing in cold climates. National Bureau of Standards Report 8905.

Schaefer, D. (1971) Installation of loose laid inverted roof system at Ft. Wainwright, Alaska. CRREL Technical Note (unpublished).

Schaefer, D. (1974) Protected membrane roofing system installation at Hanover, New Hampshire. CRREL Special Report 215, AD A005030.

APPENDIX A: TEMPERATURE AND HEAT FLOW MEASUREMENTS, ANCHORAGE AND FAIRBANKS, ALASKA, AND HANOVER, NEW HAMPSHIRE

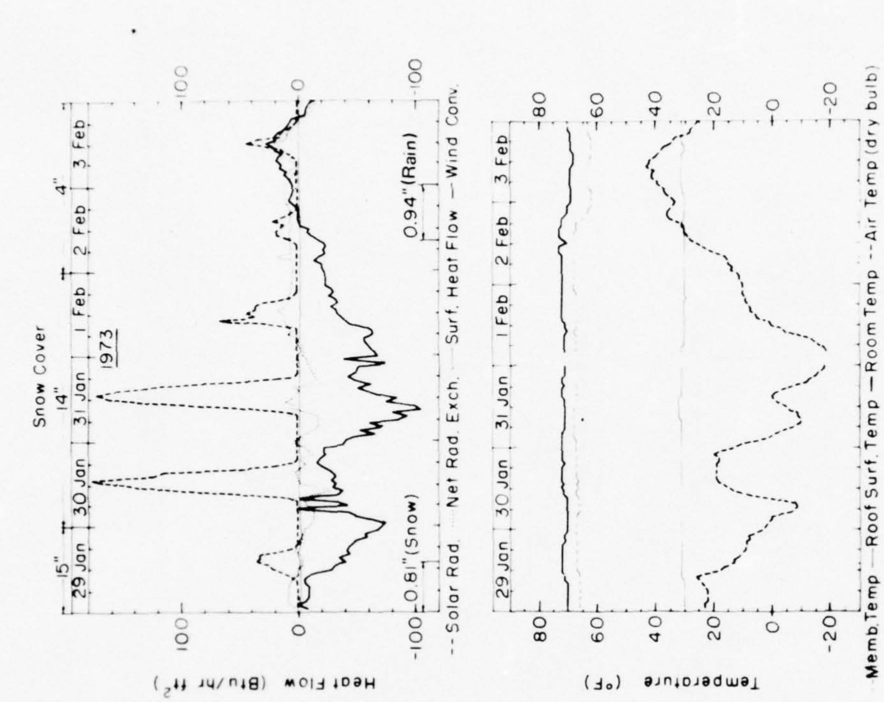

Figure A2. Temperature and heat flow measurements on the Hanover test roof, February 1973. Note the effect of rainwater and meltwater runoff on the membrane temperature during mild weather on 3 February.

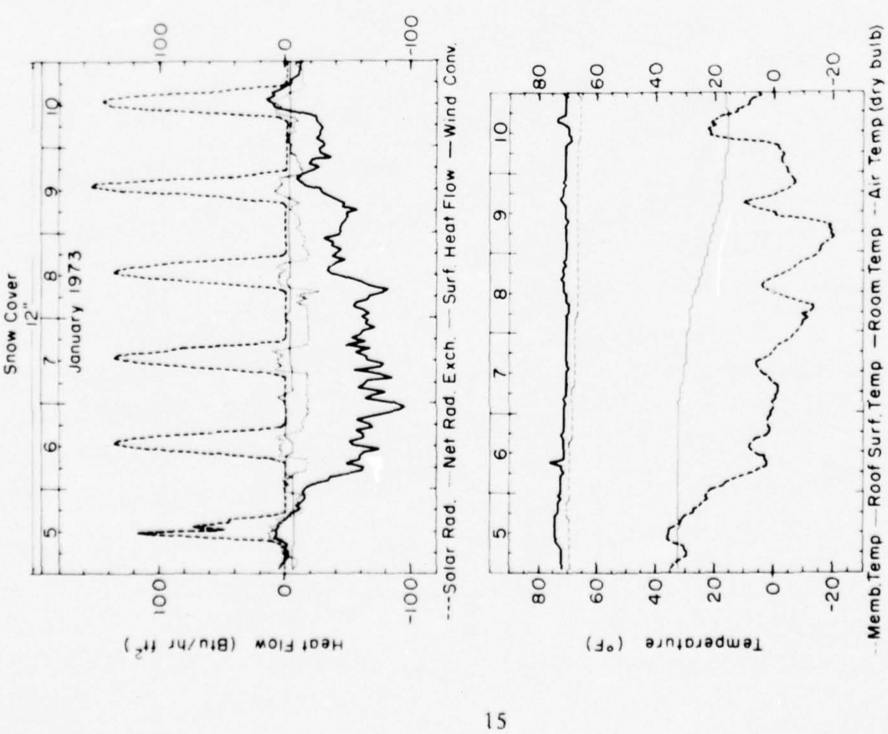

Figure A1. Temperature and heat flow measurements on the Hanover test roof, January 1973. Note the effect of the constant snow cover.

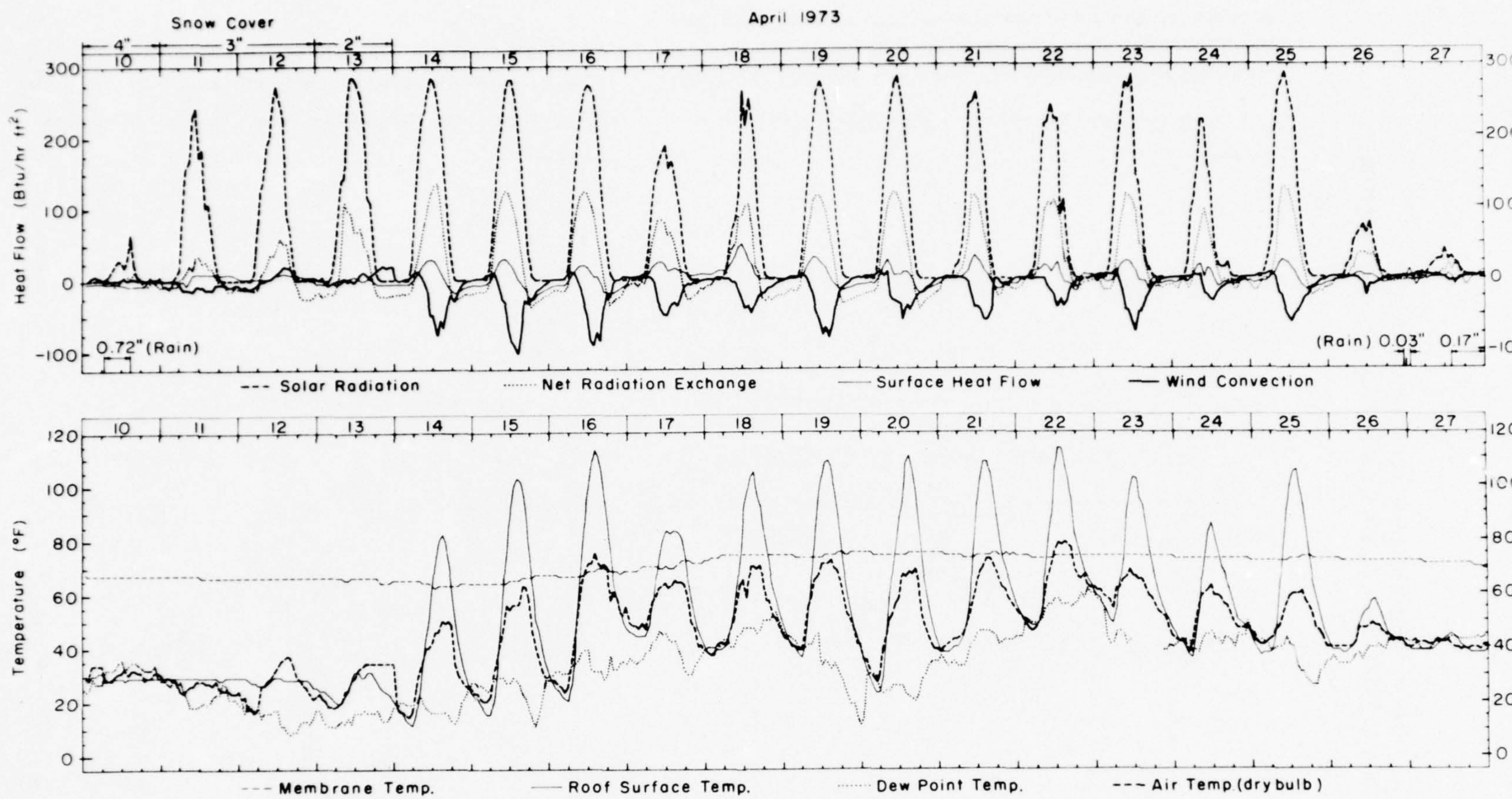

Figure A3. Temperature and heat flow measurements on the Hanover test roof, April 1973.

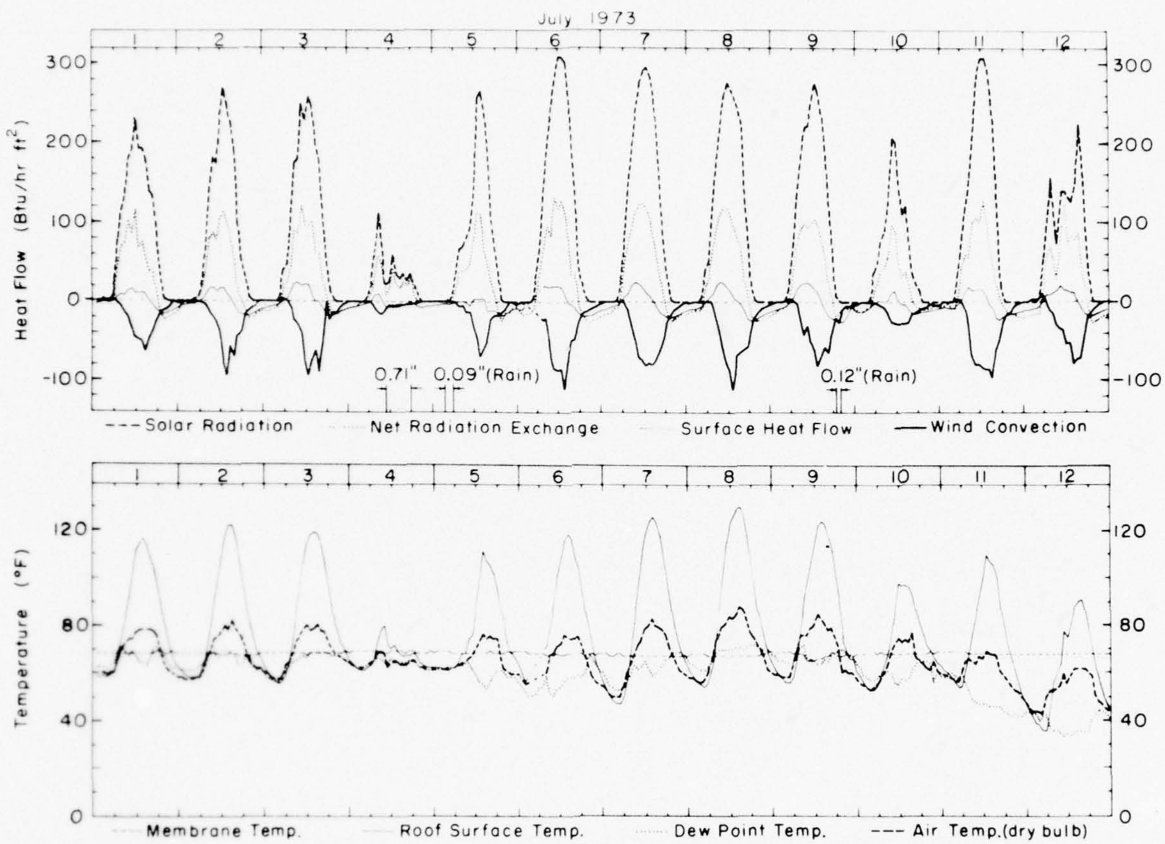

Figure A4. Temperature and heat flow measurements on the Hanover test roof, July 1973. The roof surface temperature varies by as much as 44°C (80°F) diurnally, while the membrane temperature stays essentially constant (±2°C).

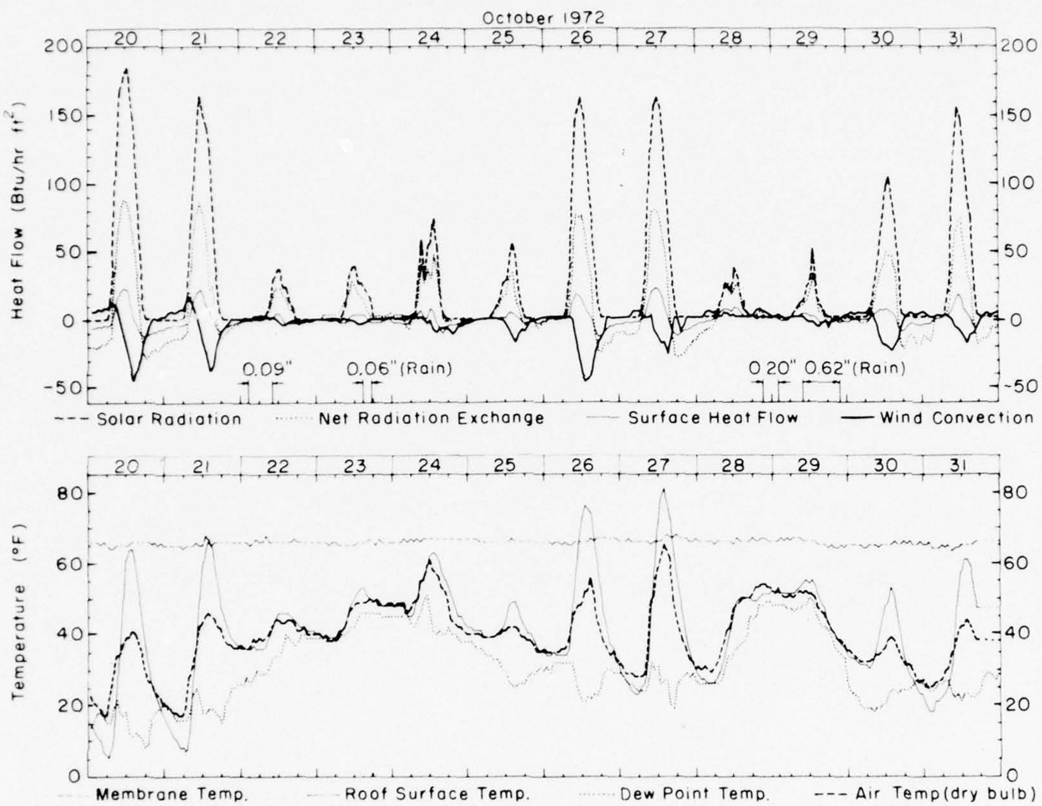

Figure A5. Temperature and heat flow measurements on the Hanover test roof, October 1972.

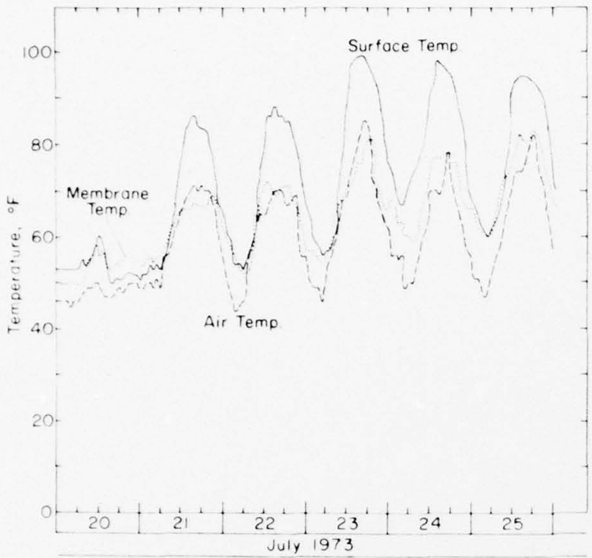

Figure A6. Temperature measurements on the Fairbanks test roof, July 1973. The test roof is on an automotive shop at Ft. Wainwright. The doors are left open during hot summer days, causing the indoor air temperature to closely parallel the ambient outside condition. The membrane temperature is sensitive to the indoor or ceiling temperature, accounting for this large membrane temperature variation.

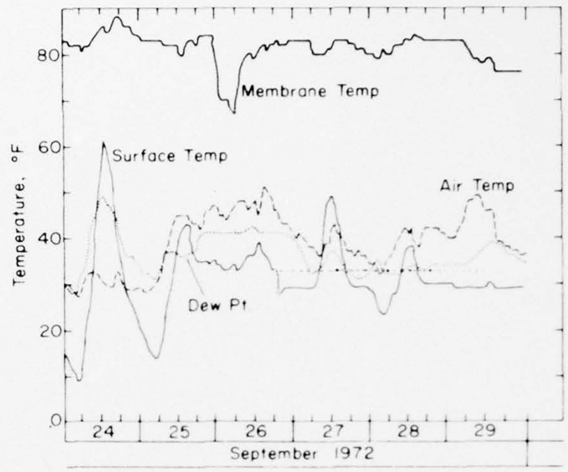

Figure A7. Temperature measurements on the Fairbanks test roof, September 1972. In the fall and winter, the doors remain closed, causing the wide fluctuations in the membrane temperature to stop.

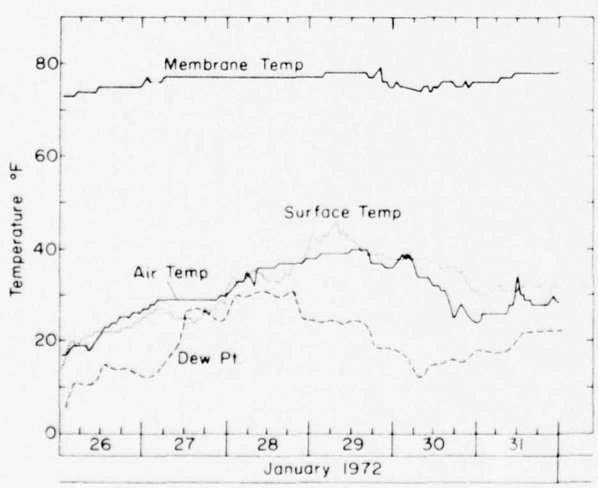

Figure A8. Temperature measurements on the Anchorage test roof, January 1972.

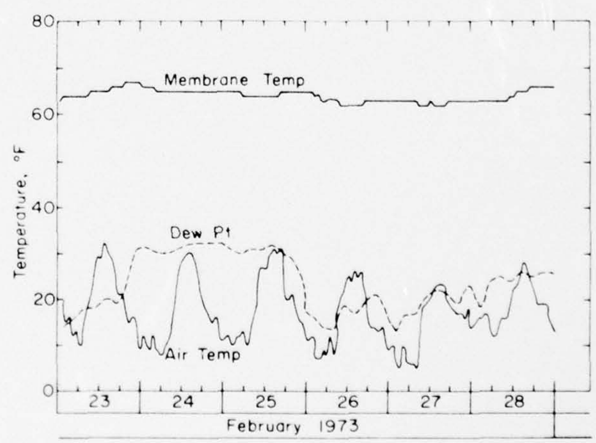

Figure A9. Temperature measurements on the Anchorage test roof, February 1973.

APPENDIX B: THERMAL EFFICIENCIES OF THE TEST ROOF, ANCHORAGE AND FAIRBANKS, ALASKA, AND HANOVER, NEW HAMPSHIRE

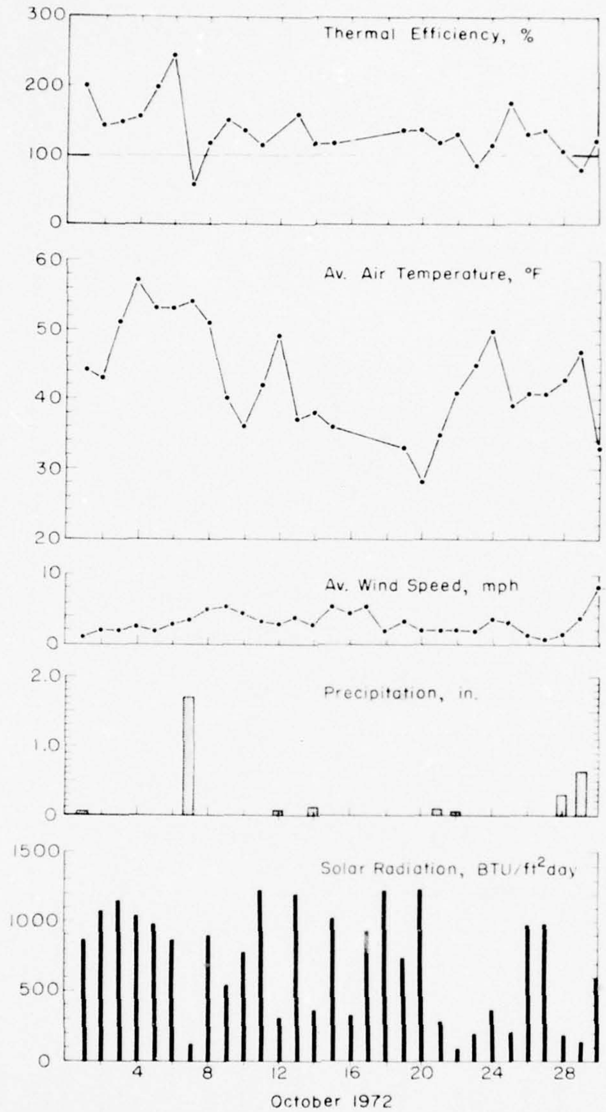

Figure B1. Climatic conditions and thermal efficiency of the test roof at Hanover, October 1972.

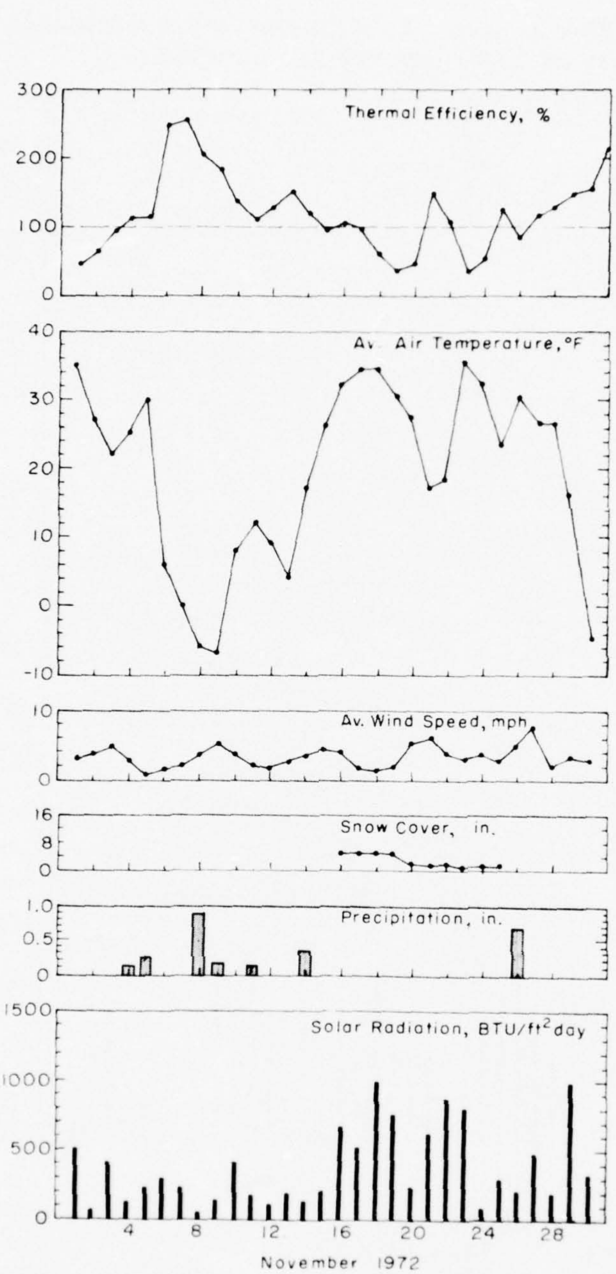

Figure B2. Climatic conditions and thermal efficiency of the test roof at Hanover, November 1972.

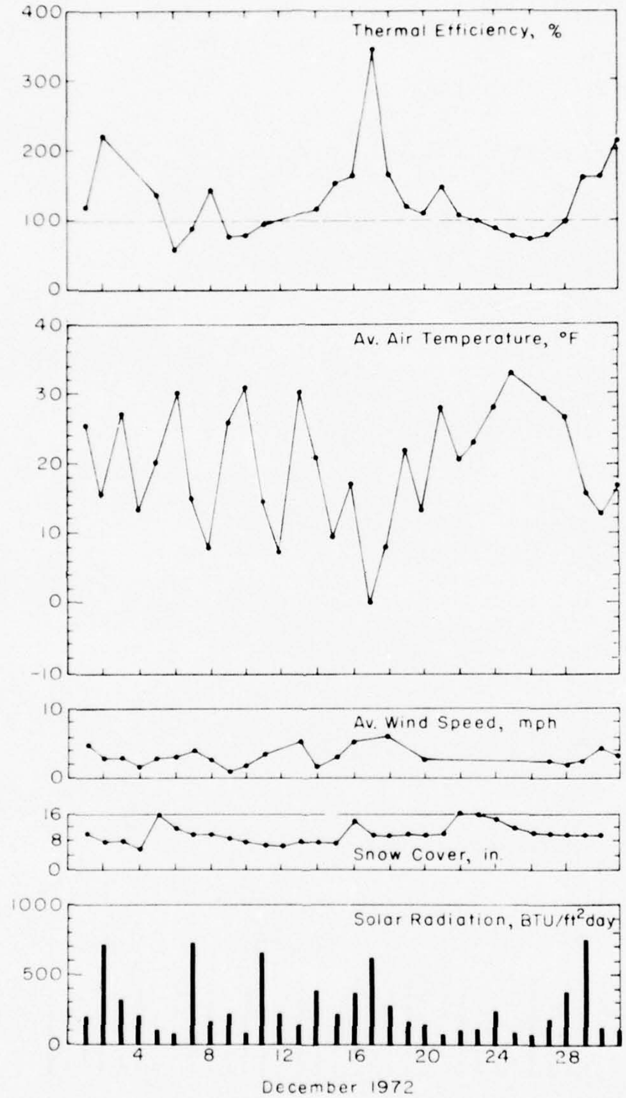

Figure B3. Climatic conditions and thermal efficiency of the test roof at Hanover, December 1972.

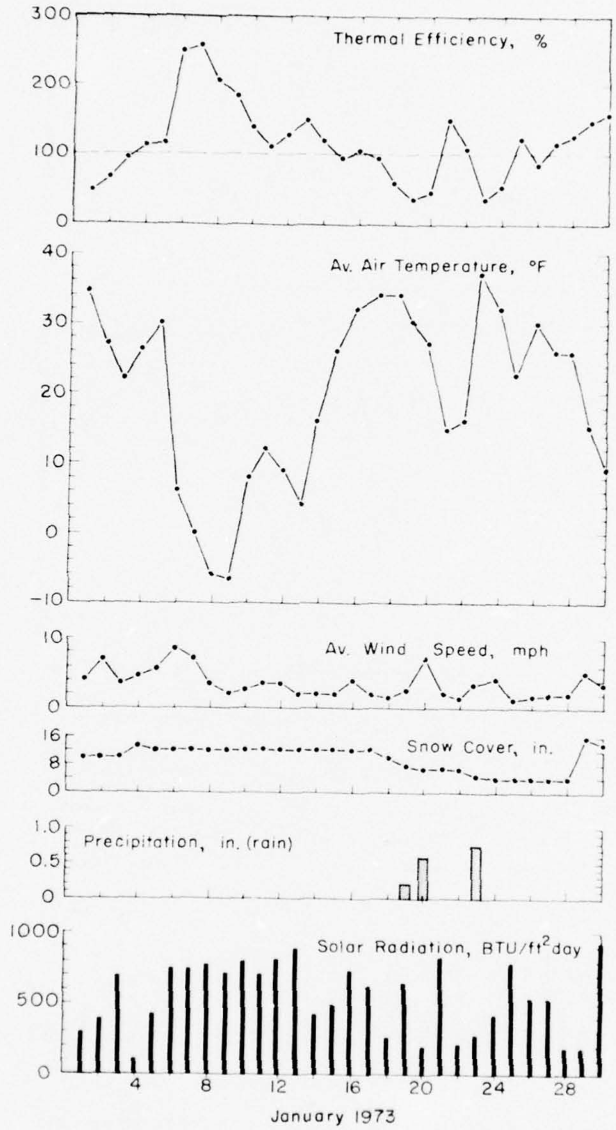

Figure B4. Climatic conditions and thermal efficiency of the test roof at Hanover, January 1973.

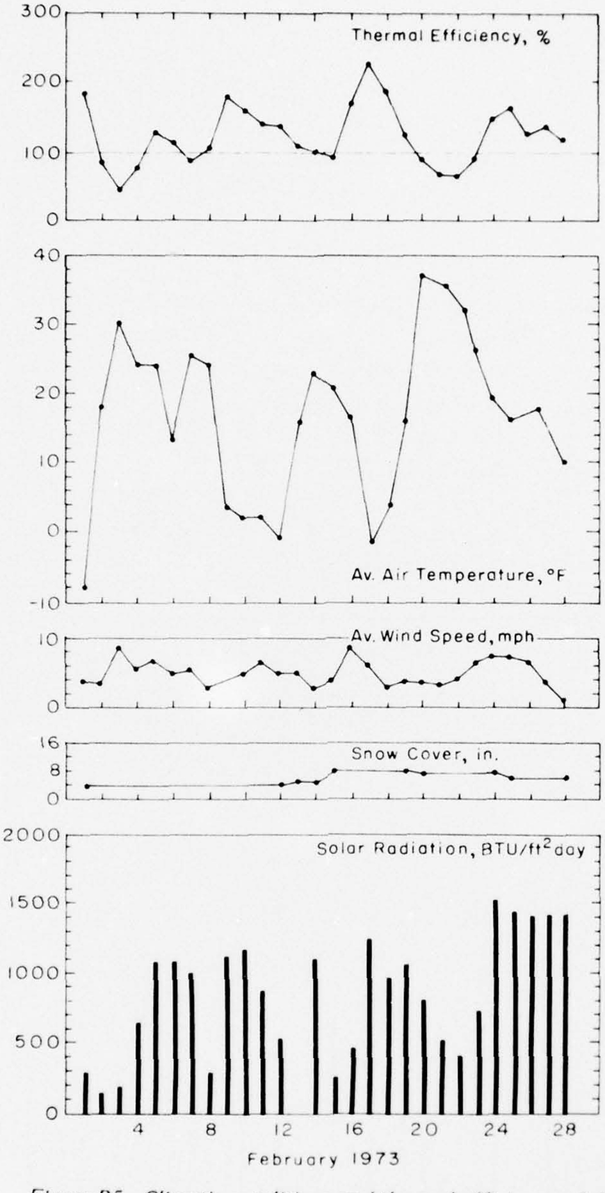

Figure B5. Climatic conditions and thermal efficiency of the test roof at Hanover, February 1973.

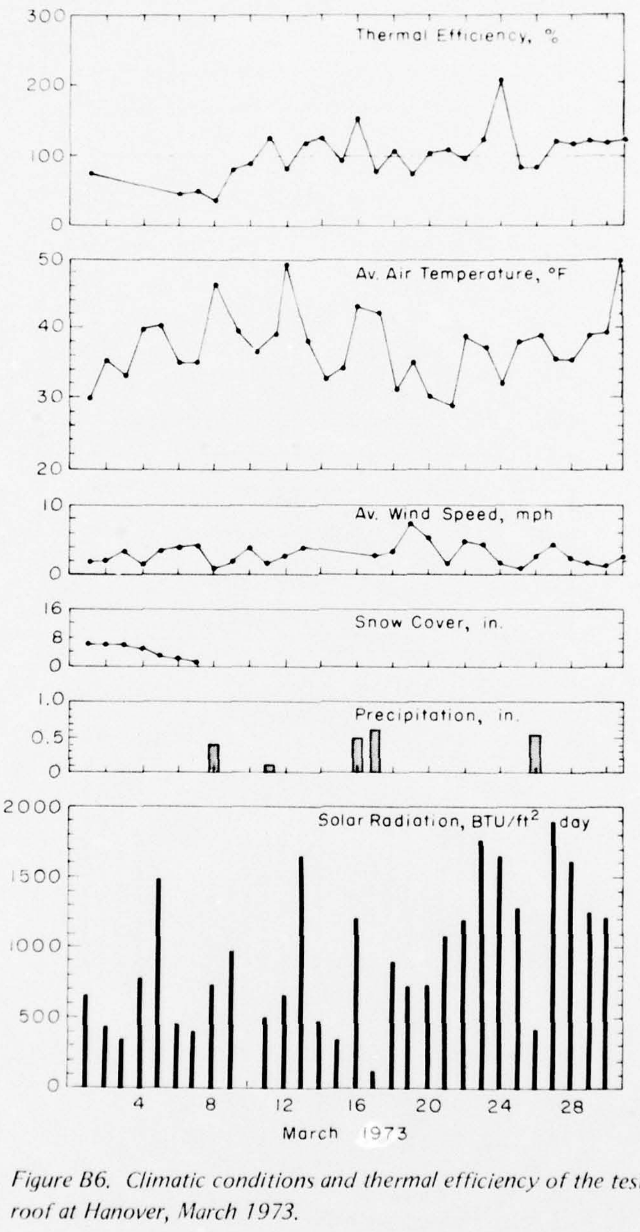

Figure B6. Climatic conditions and thermal efficiency of the test roof at Hanover, March 1973.

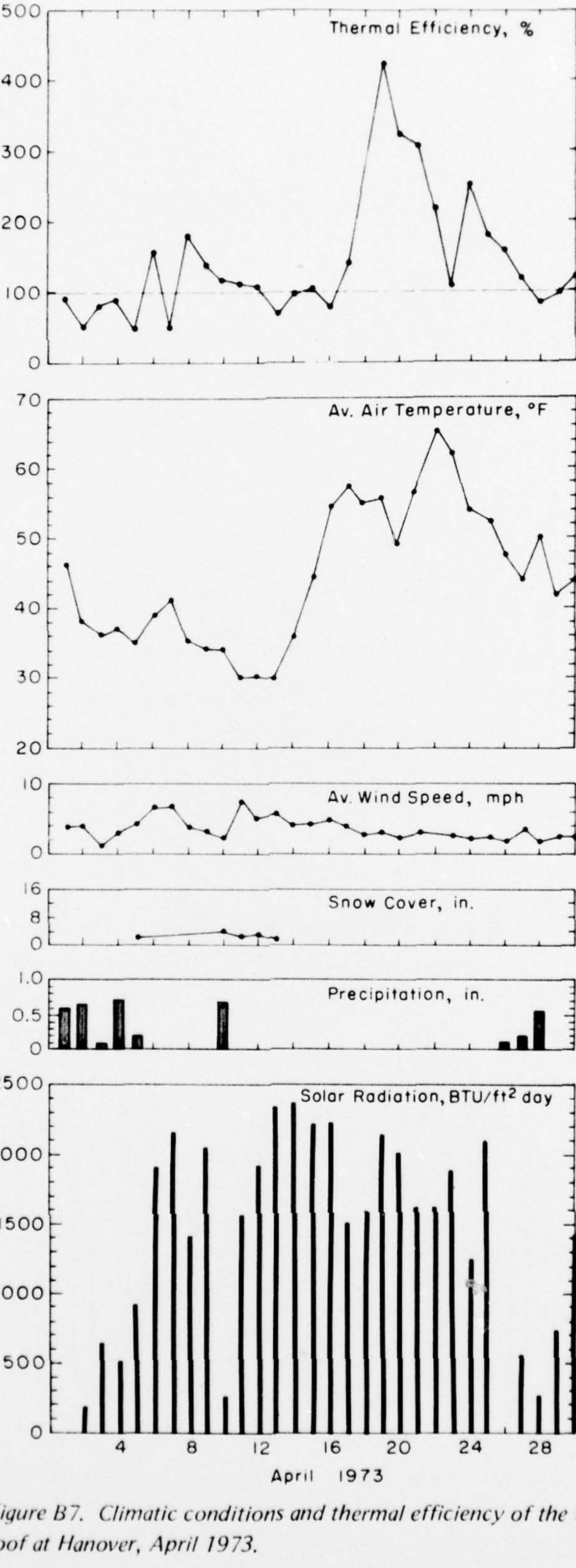

Figure B7. Climatic conditions and thermal efficiency of the test roof at Hanover, April 1973.

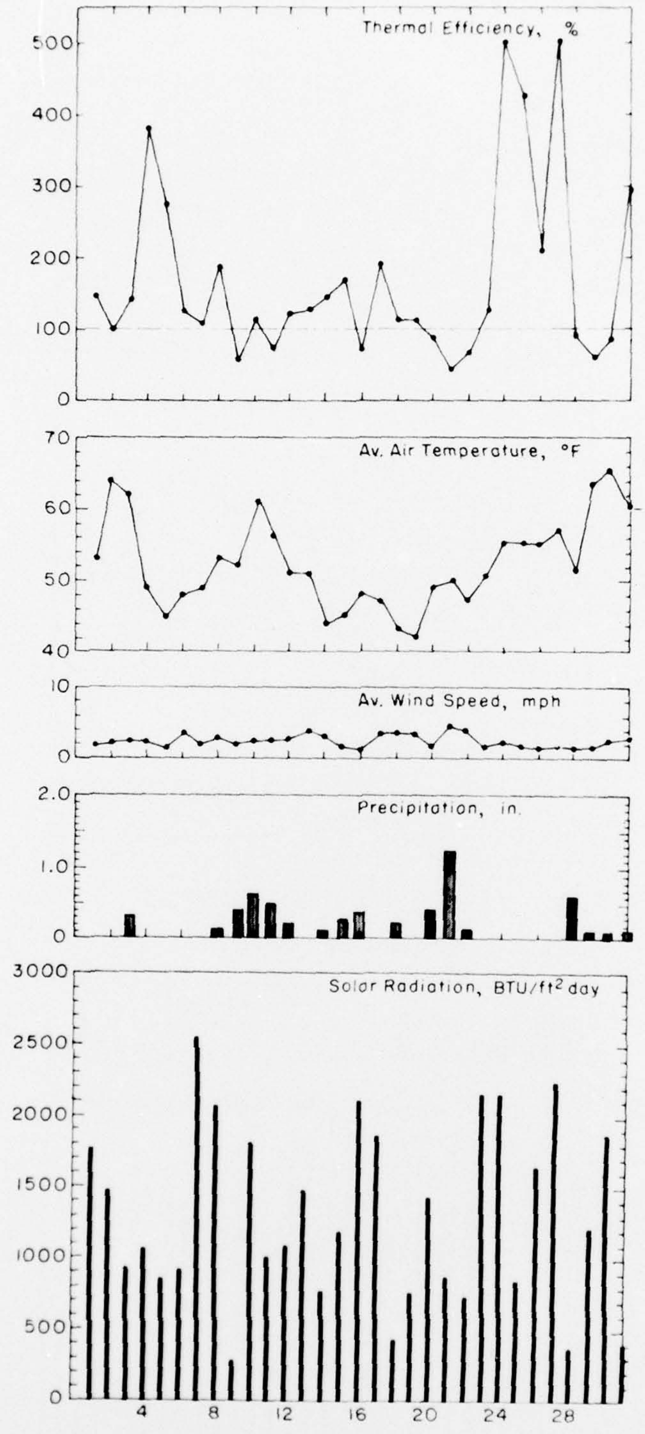

Figure B8. Climatic conditions and thermal efficiency of the test roof at Hanover, May 1973.

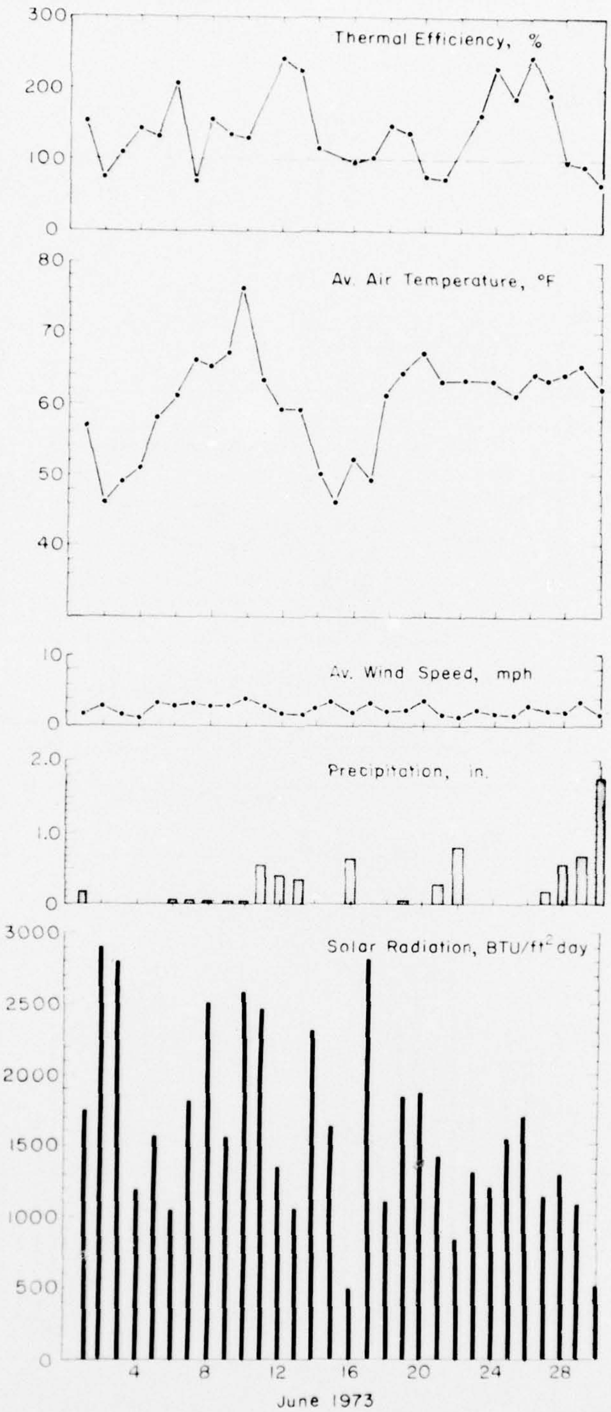

Figure B9. Climatic conditions and thermal efficiency of the test roof at Hanover, June 1973.

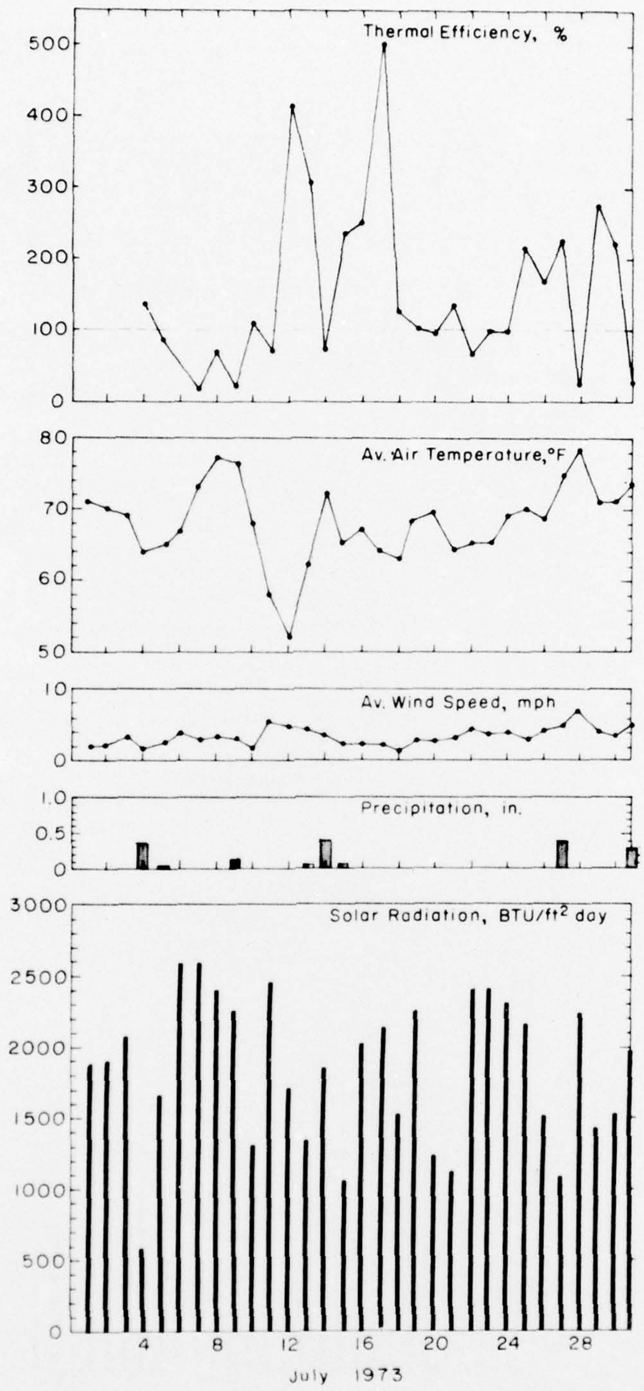

Figure B10. Climatic conditions and thermal efficiency of the test roof at Hanover, July 1973.

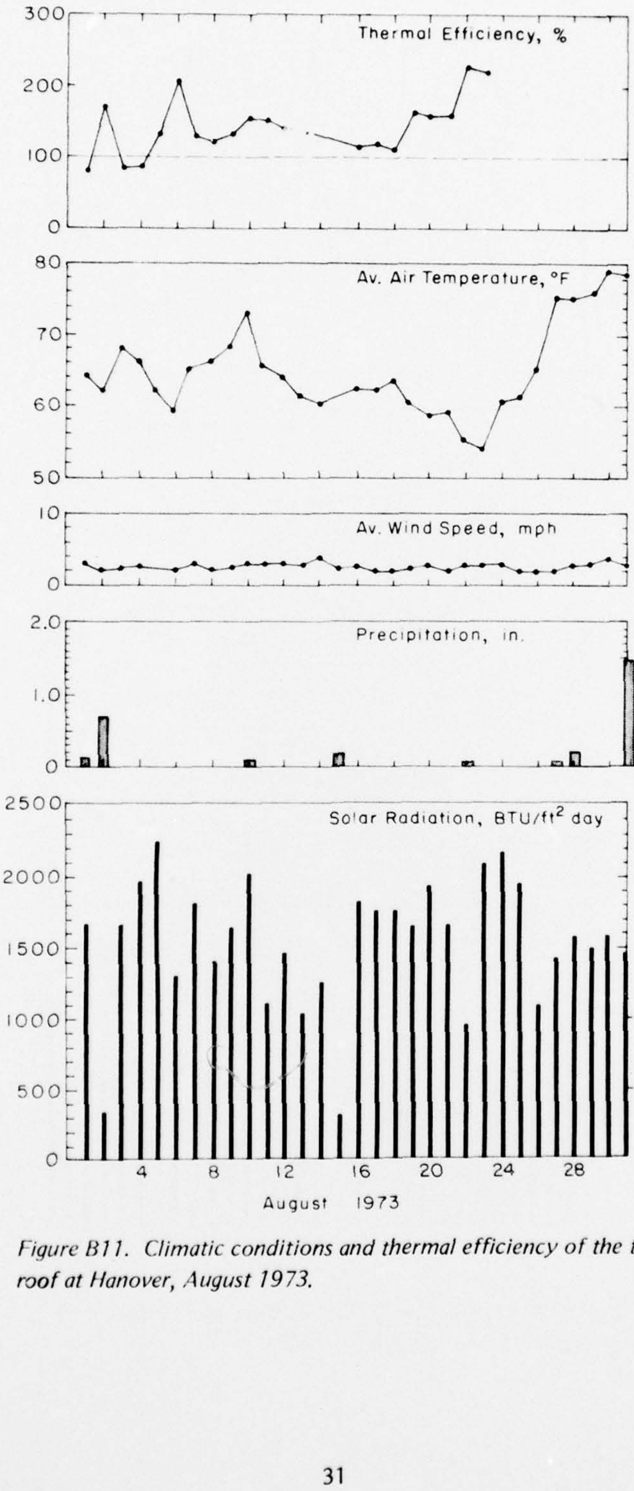

Figure B11. Climatic conditions and thermal efficiency of the test roof at Hanover, August 1973.

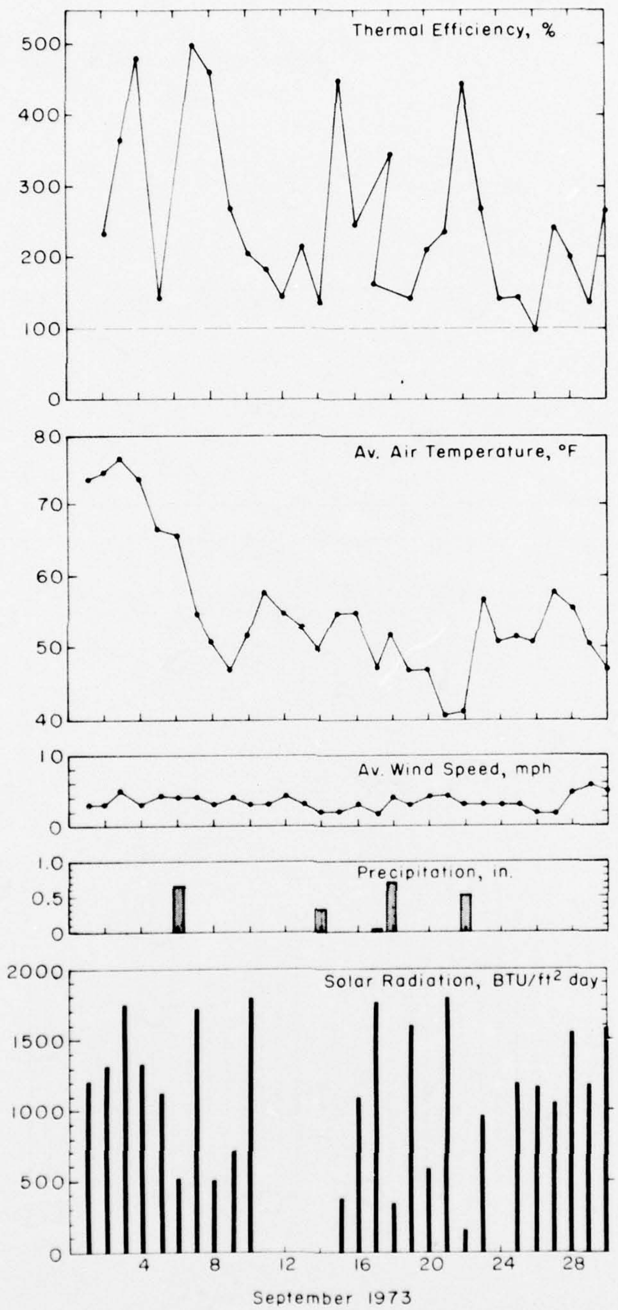

Figure B12. Climatic conditions and thermal efficiency of the test roof at Hanover, September 1973.

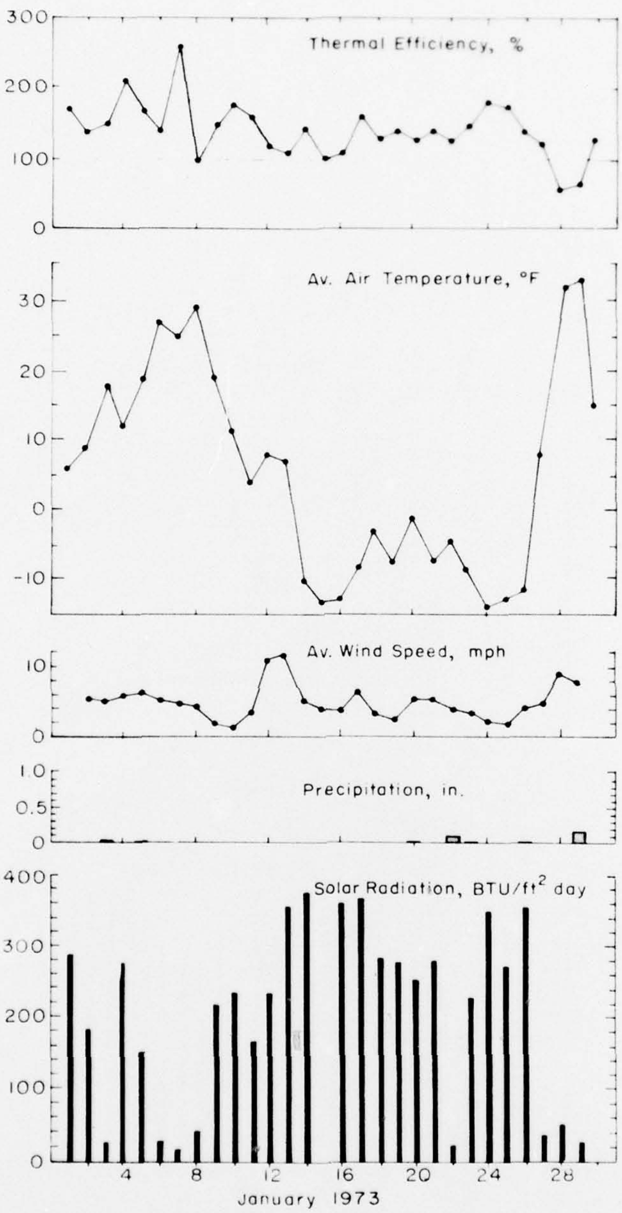

Figure B13. Climatic conditions and thermal efficiency of the test roof at Anchorage, January 1973.

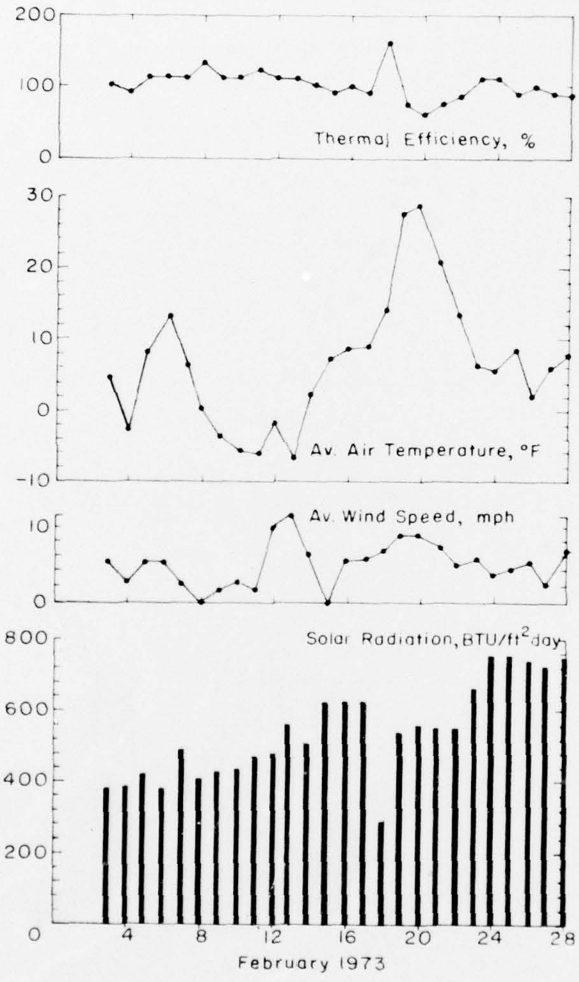

Figure B14. Climatic conditions and thermal efficiency of the test roof at Anchorage, February 1973.

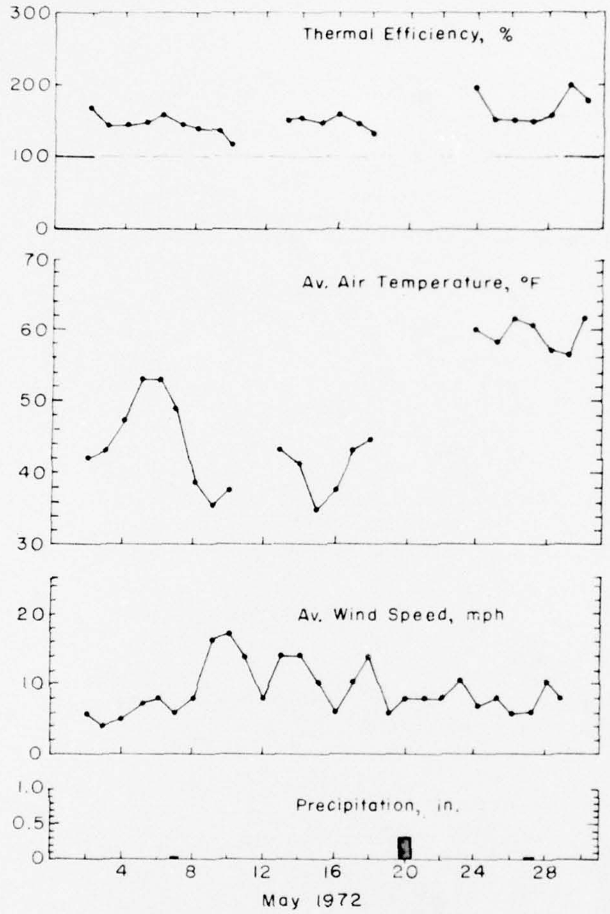

Figure B15. Climatic conditions and thermal efficiency of the test roof at Fairbanks, May 1972.

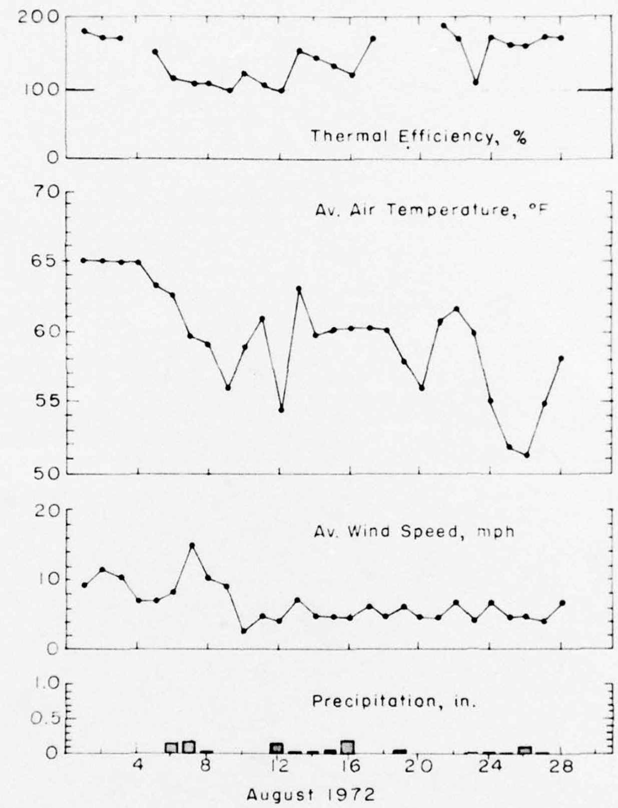

Figure B16. Climatic conditions and thermal efficiency of the test roof at Fairbanks, August 1972.

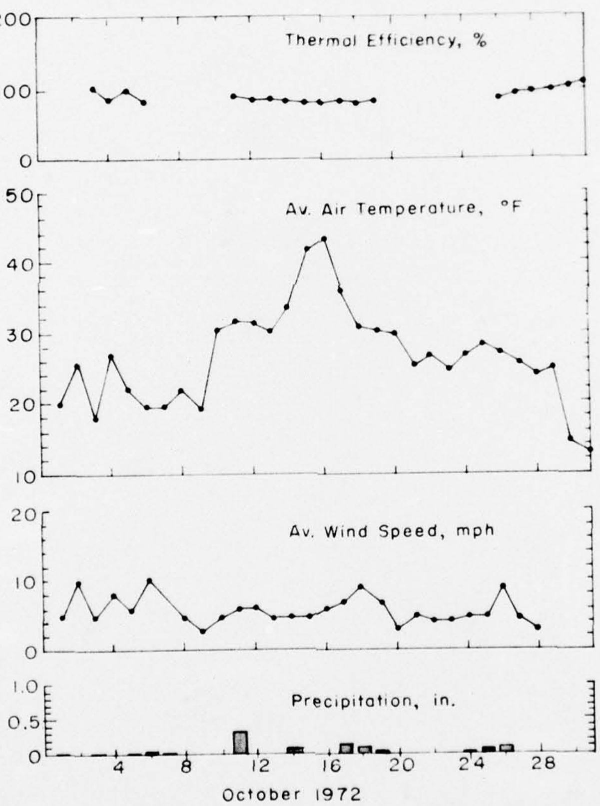

Figure B17. Climatic conditions and thermal efficiency of the test roof at Fairbanks, October 1972.

APPENDIX C: JANUARY 1973 AND AUGUST 1972 COMPARISONS OF PROTECTED MEMBRANE AND CONVENTIONAL BUILT-UP MEMBRANE SYSTEMS AT HANOVER, NEW HAMPSHIRE

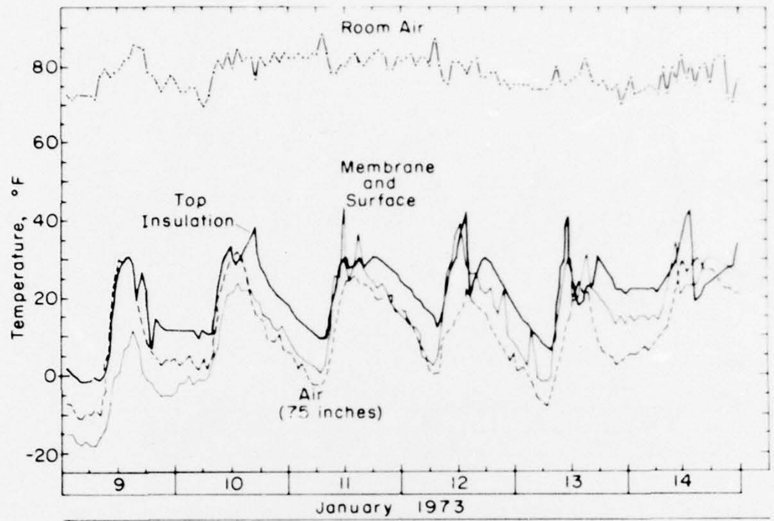

Figure C1. Hanover — conventional built-up roof. Fluctuations in temperature of built-up membrane closely follow diurnal air temperatures and generally exceed ambient air temperatures due to solar radiation. Also note the wider-than-normal fluctuations in room air temperature at the ceiling level.

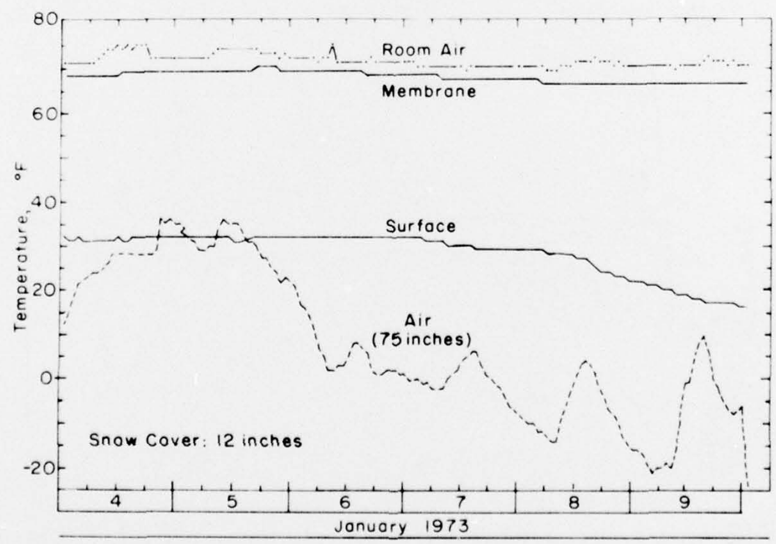

Figure C2. Protected membrane roof system. The membrane temperature closely follows the room air temperature and is not affected by diurnal air temperature. The snow cover also tends to moderate the roof surface temperature.

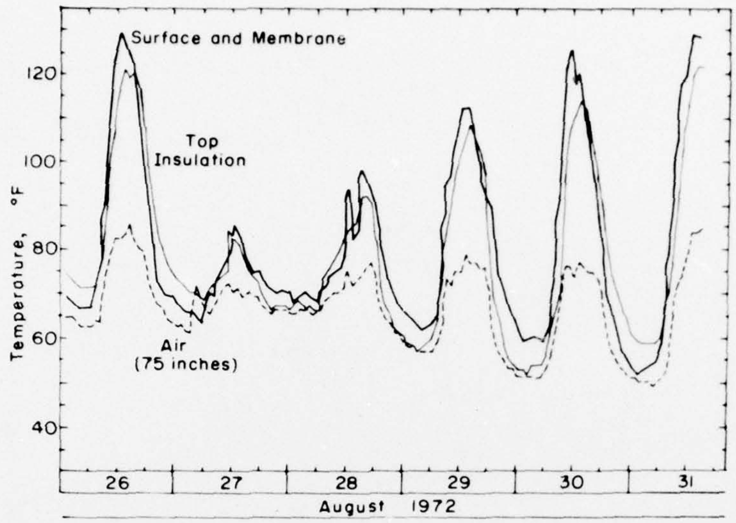

Figure C3. Conventional built-up membrane during summer conditions. The roof surface becomes much warmer than the ambient air temperature and fluctuates with the diurnal temperature. A change in surface temperature T of 70°F is not uncommon. In general, the roof surface temperature is 40 to 50°F warmer than the ambient air temperature due to solar radiation.

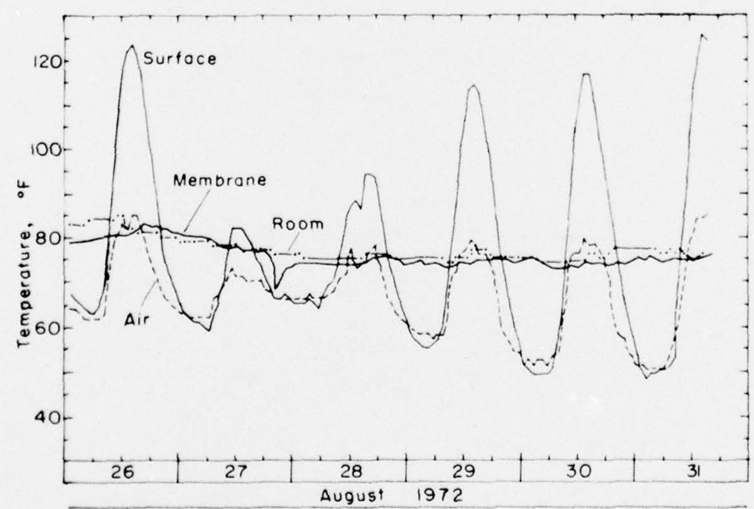

Figure C4. Protected membrane roof system for the same period as Figure C3. The membrane temperature does not fluctuate but remains thermally stable. The roof pavers (surface) fluctuate and become warmer than the ambient air temperature, but since they do not form a solid sheet, the expansion of each paver does not cause a detrimental stress on the roof system.